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Electric Propulsion for Space Vehicles

by MARCUS O'DAY

ELECTRONICS RESEARCH DIRECTORATE
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UNITED STATES AIR FORCE
BEDFORD MASSACHUSETTS

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FOREWORD

This report will portray the present status of electric propulsion of space vehicles and is limited to projects which exist only in the United States. The Report is based on discussions with scientists and engineers, and also on reports the writer has obtained on trips made to almost all of the laboratories where research on electric propulsion is taking place.

In order to clarify the title, it will be stated that thermal arc propulsion is not included. The writer defines electric propulsion as that where the momentum of the ejected material is due to the action of electric or magnetic forces acting upon the ultimate particles. If the directed momentum is due to the configuration of the container, such as takes place where a venturi is used in connection with the motor, it is classified as thermal, even though the propellant is heated by an electric arc.

An intermediate type of engine utilizes propellant heated to a sufficiently high temperature to ionize the particles, which are then contained either wholly or partially by a magnetic field. This magnetic field also acts on the particles in a manner similar to the venturi in an ordinary rocket engine. This type of propulsion can be considered either electric or thermal.

In order to arrange this report so that the reader who has very little time can obtain a general picture of the type of research in progress, the descriptions involving the fundamental principles of electric propulsion will constitute the first part of this paper. It has been intended that such descriptions be given without mathematics. The second portion of the report is composed of appendices which give more detail as well as mathematical derivations. These derivations are intended to enable the technical person who is new to this field to understand readily more detailed reports and papers describing the various types of electric propulsion devices.

It was planned to have another series of appendices, each one of which would describe the particular electric propulsion project at each company visited. However, it has been decided that in order to save time such descriptions will be given in a supplementary report.

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CONTENTS (Contd)

ELECTRIC PROPULSION
FOR SPACE VEHICLES

1. INTRODUCTION

At the present time there is no physical law known which enables an isolated vehicle to propel itself other than the law of conservation of momentum. Hence, it is necessary for mass to be ejected with a high velocity and in a direction opposite to that which it is desired the body have. The law of conservation of momentum (mass times velocity) states that the total momentum of the system must remain constant unless some external force acts upon it.

This law is used in Appendix 1 for the derivation of the rocket equation, which is as follows:

$$v - v_o = C \ln \frac{M_o}{M_o - M_p} = gI_s \ln \frac{M_o}{M_o - M_p} \qquad (1)$$

It can be seen from this equation that the change in velocity of the vehicle is directly proportional to the velocity C of the ejected material. It also increases with the mass of the propellant, M_p, but this quantity is in the logarithmic part of the equation and changes very slowly, therefore having a small effect on the motion of the vehicle. The term I_s is called the ideal specific impulse, and is equal to the ratio of the exhaust velocity to the acceleration of gravity.

1.1 The Rocket Equation

It is not feasible to obtain an appreciably higher specific impulse by chemical means, even with the use of exotic fuels. It becomes necessary, therefore, to use electrical power in order to obtain a real increase in exhaust velocity. Such an increase makes possible the use of smaller

amounts of propellant to obtain the same final velocity of the vehicle. The power to supply the electric engine for the propulsion of the space vehicle will undoubtedly come from a nuclear reactor which is carried with the vehicle on its missions.

Suggestions have been made as to the use of solar energy for this purpose, but the amount of such energy falling upon each square meter is only about 1 kw so that a very large solar collector would be necessary for this purpose. However, as will be discussed later, it may be possible to use solar energy in connection with an electric engine for overcoming drag in a satellite which it is desired to maintain at a low altitude.

One disadvantage in the use of an electric engine is that the acceleration imparted to the vehicle is exceedingly small, being estimated at about 1/10,000th of the acceleration of gravity at the surface of the earth. As a consequence, a rocket cannot use electric propulsion to leave the earth, since in order to lift a body at the surface of the earth a force must be exerted which is greater than its weight. Therefore, the acceleration produced must be greater than the acceleration of gravity. Chemical propulsion may be used to place a vehicle in an orbit, which is then very sensitive to small accelerations. One advantage claimed for the use of a small acceleration is that is is much easier to correct the course of the vehicle than if the acceleration is large and the time to make the correction small.

1.2 Uses of an Electric Engine

Electric propulsion has a number of space applications despite the small acceleration which it can impart to a space ship. These uses do not compete with chemical propulsion; in fact sometimes they are supplementary to it. The correction of the course to compensate for small errors is one example. Electric engines can provide the force to overcome atmospheric drag on a low flying satellite to enable it to maintain a constant altitude. At an altitude of from one hundred to two hundred miles there is a small retarding force acting on the vehicle, which, if there is no compensation, will cause it to fall back upon the earth. This applica-

tion is especially attractive for reconnaisance satellites which must fly at a sufficiently low altitude to obtain pictures of enemy installations with great detail.

There is another somewhat similar use for electric engines, namely, to change the orbit of a satellite to one of greater radius. Here such a motor may be utilized to increase the distance of the vehicle from the earth and also correct the orbit in order to make it circular. Communication satellites should not have eccentric orbits and it has been suggested that some of them not only be circular but be at such a distance that such satellites have a twenty-four hour period so that as viewed from the earth they seem to remain fixed in space. There are many similar applications which electric engines will have.

The most spectacular use of an electric engine is for space travel to other planets. The procedure will be to go to wider and wider orbits and finally leave in the direction of the planet in question. In this case the time will be long: a trip to Mars is estimated at 400 days (3.456×10^7 sec). The most efficient use of power and propellant will be to program the acceleration and a computer may be necessary to determine how to do this.

In order to show how practical electric propulsion is for long trips, consider a trip taking 100 days (8.64×10^6 sec) and a constant acceleration equal to 10^{-4}g. The vehicle leaves its orbit with a velocity of 25,000 ft/sec. Using the formula $v = v_o + at$, it is seen that $v - 25,000 + + 32 \times 10^{-4} \times 8.64\ 10^6 = 52,648$ ft/sec.

1.3 Effect of Mission on Selection of Specific Impulse

Much has been written in the last two or three years concerning the effect of the mission upon the selection of the specific impulse. It is not possible to increase the specific impulse without limit.

As is usually the case, an engineering compromise must be reached between the desirability of obtaining a very high specific impulse and the desirability of having a minimum amount of weight in the power supply. The word weight is here used in place of mass, since the important problem is the fuel required to place the propellant, the power supply, the

vehicle and the payload in orbit from the surface of the earth. It has been found that approximately the weight of a power supply is directly proportional to the power which it can furnish.

Now, a high specific impulse (or exhaust velocity) is obtained by using a large amount of power, which means that the square of the exhaust velocity is proportional to the weight of the power supply. A saving in weight is due to the fact that a very small amount of propellant is used; therefore, the compromise is between the saving of weight of the propellant and of the power supply. One will not make a large error if he designs the motor with a specific impulse such that the weight of the propellant used in the entire mission is equal to the weight of the power supply. It can be stated that for long trips a very high specific impulse is necessary and desirable. The state of the art in nuclear engineering determines the weight of the power supply, and as scientists and engineers increase their knowledge in this field the result will be a further reduction in the weight of the power supply. Either an engine with a higher specific impulse can be used or the vehicle can carry a larger payload.

2. SOURCES OF IONS

2.1 Cesium Ion Source

Perhaps the most critical problem to be solved in electric propulsion is the selection of the proper source of ions or plasma. In the case of the ion engine, a large majority of experimenters are using positive ions formed by the passage of cesium vapor over the surface of heated tungsten at a temperature of from 1200° to 1500° K. This method of producing positive ions is especially efficient if the time rate of flow of the cesium is not too great. It depends upon the fact that the ionization potential of cesium vapor is less than the work function of tungsten. When an atom of cesium comes in contact with the tungsten surface its outermost electron becomes entrapped and cannot leave since the ionization potential of the cesium atom is too small to hold it. The atom therefore exists as a positive ion and the electron is left on the tungsten where it passes from the electric circuit to the power supply. Efficiencies of the

order of magnitude of 99.7 percent are claimed for this method of producing ions. See Appendix 2 for more details.

Cesium is a very rare element and it is very doubtful if sufficient quantities are available for propulsion of space vehicles. Many of the experimenters working in this field expect ultimately to use potassium which is very common. However, there are a great many difficult problems to be solved in the development of an ion engine; and the engineers are unwilling to add to them by using a new propellant.

2.2 The Bombardment Ion Source

There are a few laboratories working on ion propulsion which do not use cesium vapor. One of these laboratories uses a so-called bombardment source, in reality a low pressure arc with mercury vapor. Both mercury and cesium ions are very massive. This is a great advantage since the charge-to-mass ratio, which is small, helps in neutralization of the beam. This type of ion source is termed a Plasmatron, and if it is used in connection with a magnetic field it is called a Duo-Plasmatron. It was invented by a German engineer by the name of Von Ardenne. Other laboratories that are employing this type of source are those of the Convair Corporation at Fort Worth, Texas, and the Ramo Wooldridge Corporation in Cleveland, Ohio.

The following description of this source was provided by the Goodrich High Voltage Engineering Corporation. Electrons from a heated cathode to the left of the source in Fig. 1 (not shown in the diagram) are accelerated in such a manner as to produce a low-pressure arc. This arc plasma passes through a hole in the second cathode where it is concentrated by the action of a magnetic field. This field is increasing in intensity toward the right, and as a consequence there is a high probability that electrons will be reflected since they will be striking the magnetic field at a number of angles greater than the critical angle. For an explanation of this effect see Appendix 3.

The plasma and some electrons then pass through a small hole in the tungsten insert which faces an extractor electrode which is maintained

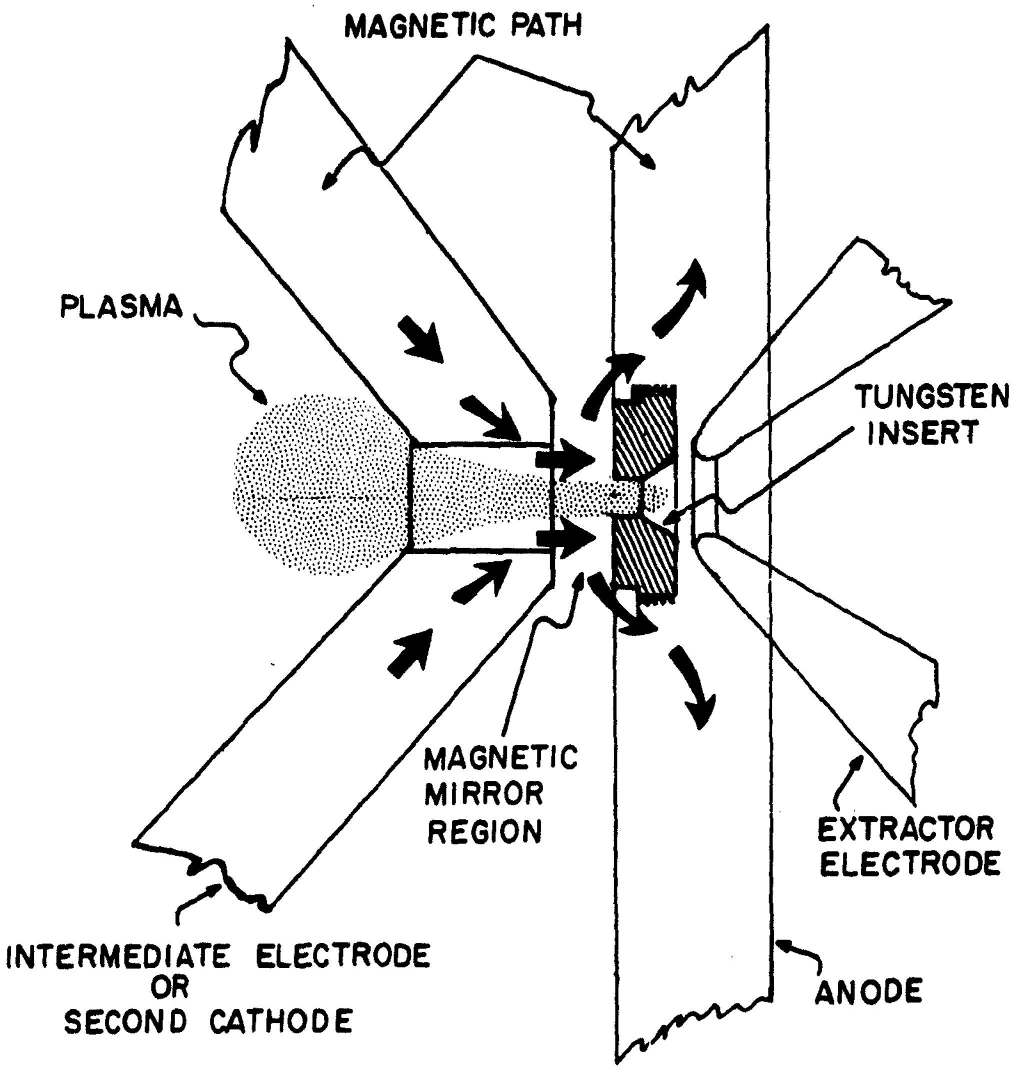


FIG. 1. Plasmatron source (Goodrich High Voltage Engineering Corp.)

at a high negative potential, greater than 50,000 v. The effect of this negative field is such as to repel any electrons which have come through with the plasma causing them to reenter the original space behind the second cathode. These electrons and those which have been reflected by the magnetic field tend to oscillate in the region to the left of the figure, thereby increasing the time available for collisions. As a consequence, the arc region becomes a very good source of ions. These positive ions are accelerated by the extractor to a high velocity, pass through an Einzel electrostatic lens, and are focused into a region where neutralization of the beam is effective.

At the present time this chamber contains a calorimeter which is used to measure the power of the beam. Later this calorimeter will be replaced by another chamber containing neutral vapor of the same type of atoms as the ions. This vapor may be at rest or in a jet which intersects the beam of ions. In any case, it is expected that upon collision of a fast ion with a neutral atom it will be possible for the ion to capture an electron from the atom causing the latter to be a slow-moving ion, and allowing the neutral atom which was originally the fast ion to leave the chamber with a high velocity.

The slow-moving ion drifts over to the side of the vessel and gives up its charge. The fast-moving atom leaves the chamber in a manner similar to the exhaust of an ion engine in a space vehicle.

This source, in a high voltage accelerator is especially susceptible to erosion and sputtering, and presents a very serious engineering problem as a result. The starting cathode for the initial production of the arc does not require current to heat after the arc has been formed. Bombardment by the ions and electrons is sufficient to keep it emitting electrons thereafter.

The Duo-Plasmatron will provide very large currents compared to the cesium ion source and it is comparatively easy to obtain currents in excess of 100 ma.

Values for the operation of this source in argon are given in Table 1. Figure 2 is a picture of the component parts. The alignment of the parts

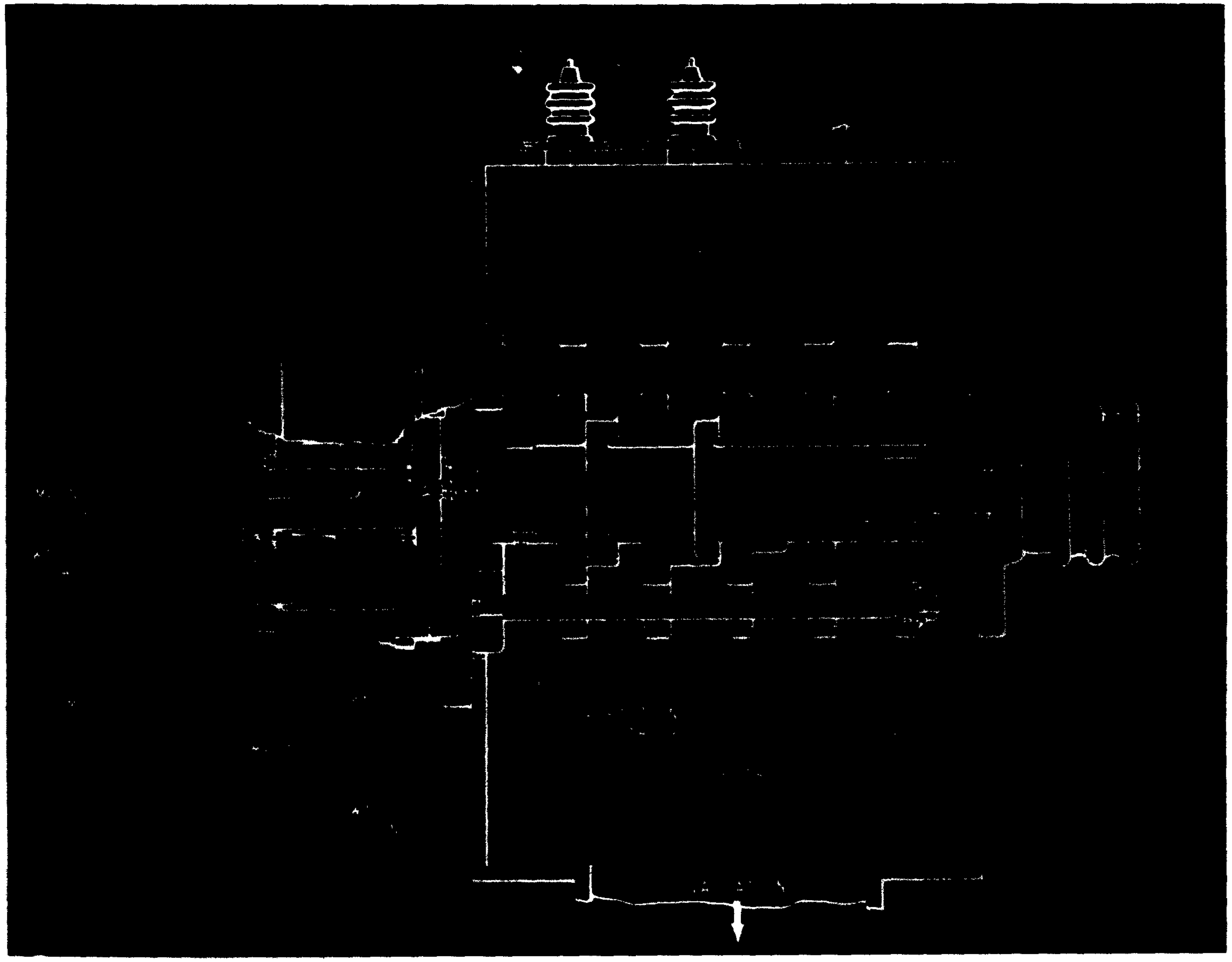


FIG. 2. Component parts of the Duo-Plasmatron.

TABLE 1. Typical Source Operation With Argon

Arc Voltage	28V	Magnet Voltage	10V
Arc Current	3a	Magnet Current	1.25a
Filament Voltage	1.5a	Filament Current	8a
Source Power	108 watts		
Extraction Voltage	18 kv		
		<u>Power Efficiency</u> = 95 percent	
Beam Current	111 ma		
Specific Impulse		30,000 sec	
Thrust		1.34 grams	

is very critical and the spheres shown in the figure are part of the alignment structure. In this source one of the problems is concerned with erosion and the difficulty is accentuated if the alignment is not exceedingly accurate.

2.3 The Penning Ionization Gauge Source

Another device for the production of ions is called Penning Ionization Gauge source and is usually written PIG. This source is being studied by two laboratories: the Aero Jet Corporation in Azuza, Calif., and the United Aircraft Corporation Laboratory in Hartford, Conn. The following description is furnished by Dr. Meyerand of the United Aircraft Corporation.

The operation of the Penning discharge plasma source may be described (see Fig. 4) by considering the trajectories of electrons emitted from the heated cathode. The electrons are accelerated toward the positive cylindrical anode by the positive potential which is applied to it by the power supply. The axial magnetic field produced by an external solenoid constrains the motion of the electron so that it is parallel to the axis of the source and prevents the electrons from being collected by the positive anode. As the electrons leave the region of the anode, which is an equipotential region, they experience a decelerating electric field produced by the grounded electrode (a second cylindrical ring) and their axial motion is stopped. The electrons are once again accelerated towards the anode and are decelerated in the vicinity of the filament which is grounded. In this manner they oscillate back and forth with their

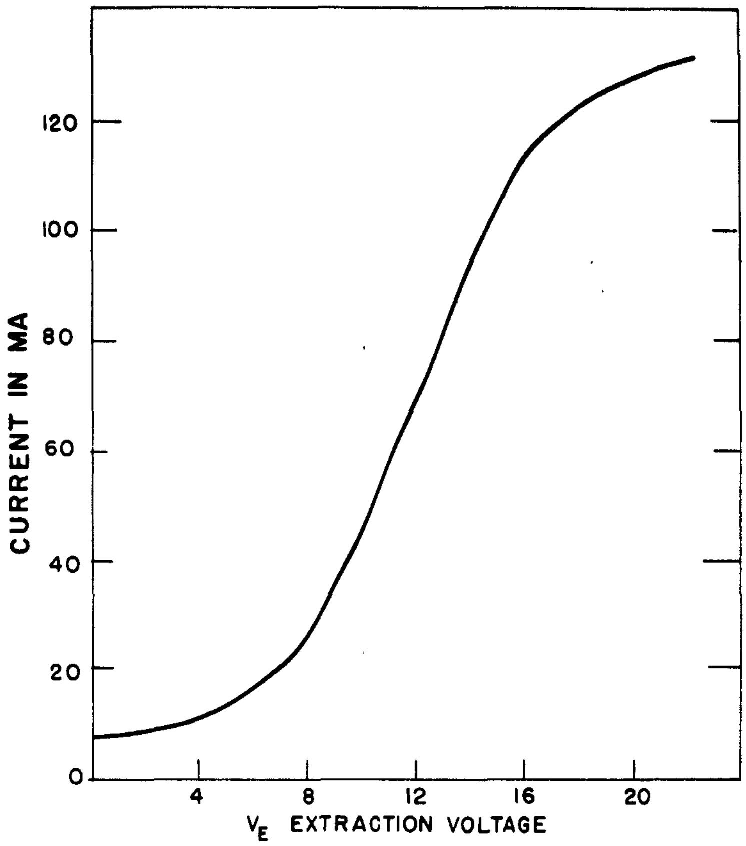


FIG. 3. Graph showing typical source operation with argon.

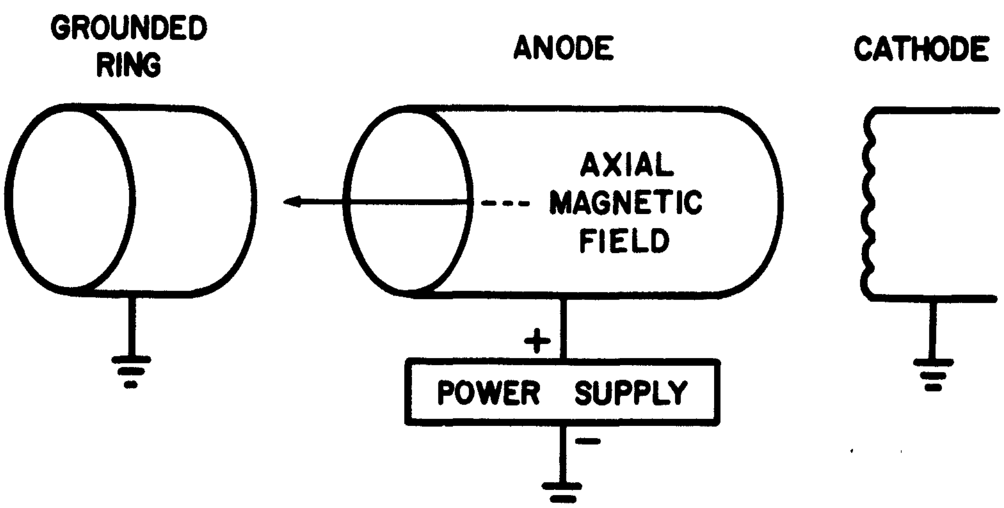


FIG. 4. Penning discharge-electrode configuration.

velocity vector parallel to the B field. If gas is now injected into the source at a low pressure such that the mean free path of the electrons is still large by comparison with the dimensions of the source, the electrons will continue to oscillate but will experience collisions with the gas atoms. Since the kinetic energy of the electrons is of the order of the voltage applied to the anode (a few hundred to a thousand volts) the electrons have sufficient energy to ionize the gas. As the electrons are oscillating in a potential well the ions will see a force exactly opposite to that of the electrons. Thus, the same electric fields which accelerate the electrons and cause them to oscillate eject the ions from the source. If the potential in the plasma in the region of the grounded ring is still slightly positive, electrons will be ejected from the source along with the ions forming a space-charge neutralized beam.

2.4 Solid Colloids

It is possible to have positively charged particles with a mass which is very great compared with that of ions. These aggregates of molecules are called colloids and are accelerated in an electrostatic field in the same way as the ions. Both liquid colloids and powdered solid material are being used. The hope behind the experiments with solid particles is that this material may also be found on the moon in suitable form for propulsion. If so, on a lunar trip a propellant need not be carried for the return trip of the earth. One very serious disadvantage in the experiments so far with solids is the discrepancy in the charge-to-mass ratios. Unless some method can be found for the production of particles of a uniform size, this type of engine does not show great promise. One of the companies which proposes to enter this field does so because its engineers believe that in connection with their work on synthetic rubber they can produce solid particles of uniform size and mass.

2.5 Liquid Colloids

Several Organizations are experimenting with liquid colloids. An oil is forced through a hollow needle, forms a spray as it leaves it, and in the process acquires a positive charge. The size of the small oil

particle is determined by the charge on it and the surface tension of the oil. Work of this type has been performed at Aerojet Corporation, Ramo-Wooldridge, and is contemplated at Rocketdyne.

3. SOURCES OF PLASMA

The discussion so far has been on the type of sources to be used for ion and colloidal engines. However, a very large part of the work being carried on in the country is concerned with plasma propulsion devices, plasma being defined as a gaseous electrical discharge composed of equal numbers of positive and negative ions. A plasma as a whole is neutral although it is composed of electric charges upon which electromagnetic fields can act. Several different materials and methods for the production of plasmas have been tried. These are

1. The exploding wire.
2. Erosion of electrodes.
3. The electric arc.
4. Gas or vapor.

3.1 The Exploding Wire

If a large capacitor bank charged to a high voltage is suddenly short-circuited by a fine wire, the latter vaporizes with extreme speed and in so doing forms a plasma. Usually the geometry is very convenient, especially for laboratory experimentation. The material can be controlled by a proper selection of wires. It is easy to form the plasma at the proper place so that it can be accelerated and form the propellant of a plasma engine. Unfortunately, large heat losses occur so that this method does not result in an efficient engine.

3.2 Erosion of Electrodes

One of the laboratories which had been using exploding wires now obtains the plasma from the erosion of large electrodes. This method has the advantage that a large number of shots can be fired in succession without any replacement of material. Usually a very small amount of gas is introduced between the electrodes to initiate the discharge. This laboratory is enthusiastic about it.

3.3 <u>The Electric Arc</u>

Since an arc is a low-voltage discharge in ionized gases it has most of the characteristics associated with a plasma. This can be the starting point in obtaining a more concentrated discharge. The ease of creating a plasma in this manner has caused several laboratories to use it in their initial experiments with a plasma engine.

3.4 <u>Gas or Vapor</u>

Gas or vapor can be introduced periodically in the vicinity of the electrodes and is ionized by collisions with ions and electrons. Once ionization is started the process is usually cumulative, and a very intense discharge takes place if the voltage is sufficiently high.

One difference between the experiments on ion engines and plasma motors is that the former are usually run continuously. On the other hand, the plasma devices are usually pulsed, although some laboratories have continuous operation of plasma engines. The disadvantage of pulsed systems is that the associated capacitor bank is too heavy. However the writer is informed of a breakthrough in this field which may make pulsed systems more practical.

4. METHODS OF ACCELERATION

Before discussing the methods for the acceleration of the propellant, it is well to review some rather fundamental ideas in physics. In the first place, the power supply cannot act directly upon the electric charges for it must first act upon an electric or magnetic field and the field in turn acts upon the charges. One might say that the field is a coupling mechanism between the charges and the power supply.

As shown in Appendix 4 the energy density in an electric field is equal to $E^2/8\pi$ and/or a magnetic field $H^2/8\pi$. Now a field is thought to be composed of lines of force which exist in space due to the presence of charges or currents. The number of lines of force which pass through a square centimeter perpendicular to the lines of force is called the field intensity.

There is a great difference between the case of an electric field and a magnetic field. Consider a magnetic field of 10,000 lines/cm^2. This has a certain amount of energy per unit volume, given by the formula $H^2/8\pi$. If there exists an electrostatic field which has the same energy density, it also has 10,000 lines/cm^2 This field is measured in the electrostatic system so that its intensity is measured in statvolts per centimeter. Because there are 300 v in 1 statvolt, a field of 10 000 lines/cm^2 is actually 3,000,000 v/cm.

If the assumption is made, which seems reasonable, that one can take energy out of either the electrostatic field or the magnetic field at approximately the same rate, an ion engine which uses an electrostatic field must of necessity be a high-voltage device; and plasma engines, which usually have a magnetic field for at least part of the acceleration, are of lower voltage

4.1 Electrostatic Accelerators

One of the advantages of the ion engine is that the charges are accelerated in an electrostatic field. This ordinarily results in simplicity.

A grid composed of fine wires is held at a high negative potential and this attracts the positive ions. Care must be taken that the area intercepted by the grid is a small fraction of the area of the channel through which the positive ions are being accelerated. Even so there is a fair amount of erosion and destruction of the grid wires According to Forrester and Speizer there are ten sputtered atoms from the grid for each 20-kv ion striking it. The expression which engineers use to calculate the velocity of the ions is very simply obtained by equating the kinetic energy ($1/2\, mv^2$) acquired by an electric charge q in falling through a potential difference V to the potential energy:

$$1/2\, mv^2 = Vq.$$

Although the currents which are passed through an ion engine are very small the voltage is very high and thus the total amount of power is comparable to other types of electric engines.

All that has been said about ion propulsion applies equally well to colloid propulsion. In this case energy is taken out of a very-high-voltage electrostatic field.

The use of high-voltage electrostatic fields is practical in space or on the moon because of the lack of an atmosphere. Here on the earth, electrostatic generators have had very little application due to the difficulty encountered with electrical breakdown. This breakdown may be due to the ionization of the air or to moisture in the atmosphere. Neither of these factors is involved in space or on the moon. Also, an electrostatic generator has a weight advantage over the more common types of electromagnetic generators used for power work. New problems may arise in the use of very-high-voltage electrostatic power supplies; however, at this time they do not seem very formidable.

4.2 Plasma Accelerators

Plasma accelerators can be divided into the following types:

1. The rail accelerator with external magnetic field.
2. The rail accelerator with selfmagnetic field.
3. The pinch.
4. The T strap.
5. The Bostick button.
6. The travelling wave.
7. The coaxial line.
8. The shock tube.
9. The moving magnetic mirror.

4.2.1 The Rail Accelerator With External Magnetic Field

In all devices in which a magnetic field causes the acceleration of moving electric charges, the force exerted by the field is perpendicular to both the field and the direction of motion of the charges. This is usually termed $j \times B$, but as used by the electric propulsion engineers the term $j \times B$ denotes a particular type of magnetic field which acts upon the current in the same way as the magnetic field of an electric motor acts upon the wire carrying the current in the armature. This magnetic

field is external to the system and can be from a permanent magnet or an electromagnet. Such a magnetic field in a rail type of accelerator is shown in Appendix 7 (Fig. 7.1). It is also proved in this appendix that if large currents are employed the effect of the external magnetic field becomes less important by comparison with the selfmagnetic field of the current.

4.2.2 The Rail Accelerator With Selfmagnetic Field

If the currents exceed 100,000 amp (10,000 emu) the complexity and weight of the external field is unnecessary and the selfmagnetic fields are sufficient to exert a suitable force on the plasma. This action is discussed in Appendix 7.

4.2.3 The Pinch Accelerator

When two wires carry a current in the same direction, their magnetic fields pull them together. One can consider a discharge to be composed of a number of filamentary currents in the same direction. The magnetic fields of these currents pull them together causing a constriction in the discharge. This phenomenon is known as the pinch effect; that is, the discharge is pinched or constricted.

Now since the plasma is a gas, if a portion of this gas is pinched perpendicular to the longitudinal axis, it causes a pressure which tends to force the gas along the axis of the cylinder. Of course, this pressure is exerted from the pinch in both directions, as shown in diagram (Fig. 5). If one can make this pinch asymmetrical, it can exert a force on the gas which causes acceleration in the direction desired. One of the very important projects concerned with plasma propulsion is based upon this phenomenon. In general, this effect is transitory and not continuous.

Another type of accelerating device to be used with the plasma engine has just been mentioned; namely the $j \times B$, where B refers to the magnetic field which is perpendicular to the current flow. This device is very similar to a dc electric motor and is shown in Appendix 7.

4.2.4 The T Strap

The T-strap accelerator is shown in Fig. 6. The magnetic fields due to the geometric configuration of the current in this case cause a large

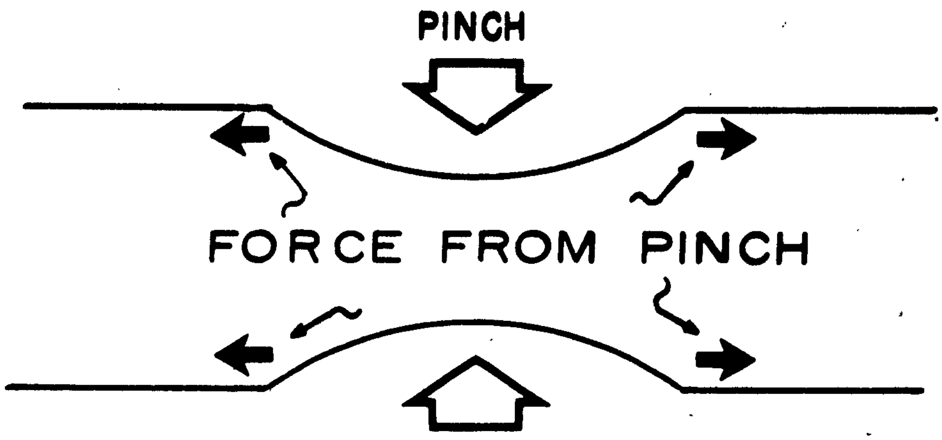


FIG. 5. Pinch effect.

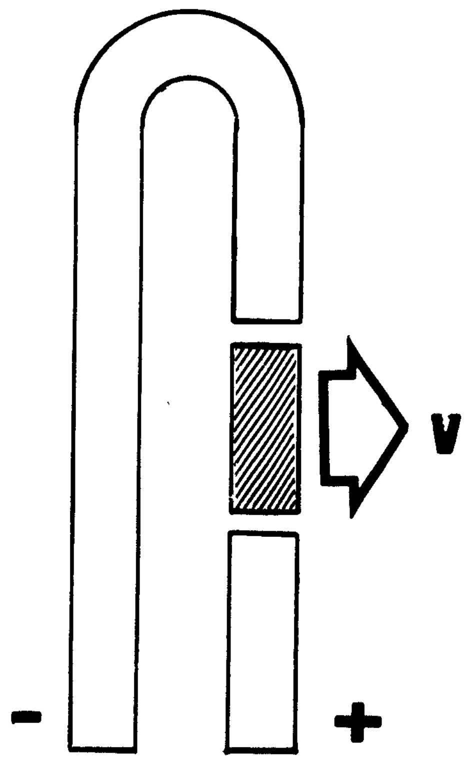


FIG. 6. The T-strap accelerator.

force to act upon the movable part of the system. As a result, it is ejected with a high velocity. A disadvantage of this accelerator is that it does not exert a continuous force but rather an impulse on that part of the circuit being accelerated since the instant this portion moves any great distance the circuit is broken.

4.2.5 The Bostick Button

Another type of impulse accelerator is called the Button Plasma Gun, used by Professor Bostick in the generation of his plasmoids. This type of accelerator is shown in Fig. 7.

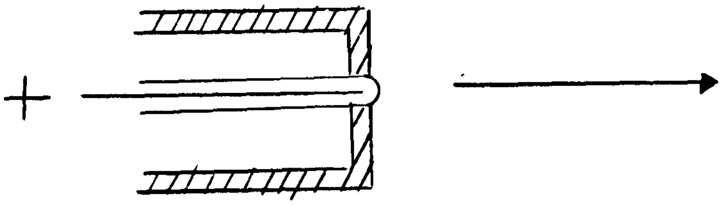


FIGURE 7

4.2.6 The Travelling Wave

A solenoidal accelerator uses a travelling wave which forces a conducting annulus along its axis. It is very similar to the so-called solenoidal type of electromagnetic gun and is easier to understand as a gun with a conducting bullet. Then it can be considered exactly the same in a plasma engine with the conducting bullet which is replaced by a plasma. If as in Fig. 8 an oscillatory current passes through the coil, it will induce eddy currents in the conducting bullet. The reaction of the mag-

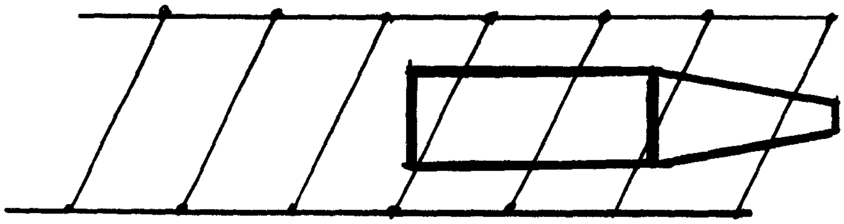


FIGURE 8

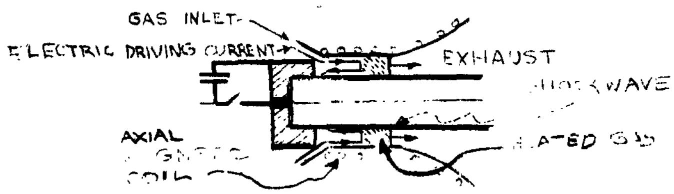
netic fields due to these eddy currents and the magnetic field of the primary currents flowing through the coil causes a force to be exerted upon the bullet. If the bullet is past the middle of the coil it will be accelerated to the right, as shown in the diagram. One of the difficulties of this device as a gun is due to the fact that only one half of the coil becomes effective. If in place of the system as described, a travelling electromagnetic wave goes down the coil, all of the coil can be utilized in the acceleration of the bullet. When this device is used for the acceleration of a plasma in an electric engine such a travelling wave does go down the coil. One arrangement has been to divide the coil into segments and connect each of these with a corresponding capacitor so that the coils and the capacitor form an artificial delay line. Another way of obtaining a travelling wave is to have precise timing of switches which discharge capacitors through each coil so as to simulate a wave going from left to right. This type of plasma accelerator holds a good deal of promise, as a very practical device in an electric engine.

4.2.7 The Coaxial Line

This device works exactly the same as the rail type of accelerator which has been described in Appendix 7. One very important advantage of using a tube is that there is no loss of plasma as is the case with the rails.

4.2.8 The Shock Tube

This accelerator is used in conjunction with a magnetically driven shock tube. This type of accelerator is shown in Fig. 9. It is formed by a discharge in a coaxial tube but not in the same manner as just described. The currents flow as indicated in the figure.



The motion of the plasma is governed by the law: if a portion of an electric circuit is free to move, it will move so as to increase the area of the circuit.

The effect of the magnetic fields is to exert a very high impulse on the plasma so that it travels rapidly to form a shock wave in the direction indicated. This method of acceleration is claimed in some laboratories to be expecially effective.

4.2.9 The Moving Magnetic Mirror Accelerator

The magnetic mirror is discussed in Appendix 3. It is possible to trap ions in a magnetic mirror, and one of the thermonuclear projects is based upon this fact. Ions are injected into a region which is bounded by magnetic fields in such a manner that they are confined in a volume formed by the magnetic field which reflects them. In thermonuclear work the ions are heated to a very high temperature in this region. It has been proposed that a similar configuration be used for an electrical engine. However, in this case the magnetic mirror is not stationary, but moves at a high velocity. As it moves, it carries the ions along with it so that ultimately when the end of the mirror collapses at the exit of the engine the ions which have acquired a high velocity are ejected. The manner in which the magnetic mirror is made to move is to have the magnetic field which creates it vary either by being pulsed in the right sequence or be produced by alternating current in the proper phase. The field moves similarly to the way it does in the travelling-wave accelerator. Since there are no moving parts in this accelerator, the field can move at a high rate of speed. The principle behind the accelerator is sound although the writer is unaware of any project where experimental work on it is being performed.

5. INSTRUMENTATION

In any experimental research, instrumentation plays a role which can hardly be overemphasized. It is almost as important as the conceptual design and the theory behind the experiment. Poor instrumentation can not only give erroneous results but can lead to false hypotheses, and perhaps even to a wrong statement of physical principles. On the other hand,

excellent instrumentation can not only give data which can test the theory but can also even lead to the discovery of new laws and principles. Scientists and engineers who specialize in instrumentation are extremely critical not only of their own work but also of the work of other experimenters. One might almost say experimental work without good experimentation and good instruments is not worth doing. Electric propulsion experiments require some specialized instrumentation which will be described below.

5.1 Neutralization of the Ion Beam

A general problem of neutralization is considered elsewhere in this report. It is necessary to determine if the ion beam has been neutralized, and to what extent. In some of the laboratories they have depended upon optical means to determine if neutralization has taken place. This procedure is based upon the assumption that an unneutralized beam is not collimated and will diverge sufficiently to be visible. A real hard vacuum that will simulate space cannot be used since enough atoms of the gas must be present to be a source of light to render the beam visible. This method is only qualitative at best and does not describe conditions in practice. Moreover, the presence of a small amount of gas can materially alter the properties of the beam, and thus violates one of the axioms of instrumentation; namely, instrumentation must measure the quantities considered under the conditions of use, and must not introduce changes in these quantities.

One method used with the ion beam in a high vacuum is to have an insulated electrode intercept the beam and to measure the rate of accumulation of charge on this electrode. A comparison between this current and the current known to be in the ion beam gives a measure of the divergence and of the effectiveness of neutralization. Of course, this current will be measured with and without the neutralization. From such measurements very important diagnostic data can be obtained.

5.2 Measurement of Thrust

The primary purpose of an electric engine is to create a thrust which propels the vehicle. The determination of the amount of such thrust is a very important measurement and gives a very large amount of information. The measurement of thrust will differ greatly in a plasma engine as compared with an ion engine. The plasma devices exert a very large force, compared with the ion engines. Consequently, it is comparatively easy to place a ballistic pendulum at the output of the engine, allow the propellant material to strike the pendulum, and thereby cause it to move. In general this motion is measured by optical means. In the case of the plasma engine, the thrust is even large enough so that the engine itself can be mounted on the pendulum and the reaction measured under the same conditions as exist in space. The writer believes that this method is foolproof and will give factual data which can be extrapolated from the laboratory to practical use.

In general a plasma engine exerts a sufficiently large force so that the thrust can be measured even though the device is pulsed. With the repetition rate known, it is possible to make simple calculations concerning the performance of the engine.

In the ion engine, the instrumentation is much more difficult since the beam does not exert a large force. The ballistic pendulum must be very light and very sensitive. In this case, it is impossible to place the engine on the pendulum. Instead the pendulum must be separate and in such a position that it catches the propellant material which is exhausted from it. It is desirable to have some auxiliary means of measuring the energy of the thrust. In several of the laboratories where ion engine research is performed, a calorimeter is also used in order to measure this amount of energy. Since usually an ion engine runs continuously and is not pulsed, a calorimeter is a natural device for such measurements. Very often it is made integral with the ballistic pendulum. Since the thrust is small, the motion of the pendulum is also small, and refined methods must be used to detect this motion. In one of the laboratories, the small displacement of the pendulum is measured by the change of

capacity between it and the fixed electrode. This change of capacity is measured in a radiofrequency circuit, and is a standard method used in other fields for measuring small displacements. The writer was told that this device was not designed especially for this particular experiment but is commercially available.

Some of the experimenters have felt that time is wasted on a ballistic pendulum measurement in the initial phases of research. The writer cannot agree with this attitude. In the work which was done in one company, for instance, competitors had stated that it was not a beam of ions which was present in the apparatus but rather a beam of electrons. However, ballistic pendulum measurements indicated that the beam under consideration was actually composed of ions, since it exerted a measurable thrust. Electron beams cannot exert a thrust which could be measured yet could heat up a calorimeter. The proper instrumentation can tell the experimenter what is actually happening in his apparatus.

5.3 Efficiency of the Engine

The efficiency of an electric propulsion device is not only important—it is critical. Many of the engines which have been proposed, and upon which feasibility studies have been made, are useless for space propulsion unless greater efficiency can be achieved, and an inefficient engine requires such a large power supply to go with it that the entire mission of the space ship becomes impractical. Not only must the efficiency be measured accurately but it must be given in terms of the energy used in propulsion by comparison with the energy available from the power supply. Different engineers have various methods for designating efficiencies but the only efficiency which means anything at all in a space vehicle is the ratio just mentioned. The measurement of the power output of an electric engine must involve the measurement of thrust, and the power output is equal to the force times the velocity. The measurement of the power input from the power supply can be made according to standard methods. In the development of an engine it may be necessary to measure the power input to the engine itself, which does not include losses in

the generating system. This type of measurement is for obtaining data to improve the engine. However, it must be kept a secret from the sales organization which must only be cognizant of the overall efficiency. In experiments which have been run so far, efficiencies in excess of 40 percent have been quoted. These have been measured only for a very short time.

5.4 Factors Which Affect Life of the Engine

Since a space vehicle with an electric engine will be operating for a very long time, the order of magnitude of over a year, and the engine will be running continuously, it is absolutely essential that any particular engine operate for this period of time without maintenance, and with an exceedingly high degree of reliability. This requirement presents an extremely difficult problem in the design of such a device. In the development work it is necessary to design means for the measurement of a phenomenon which can shorten the life of such equipment. For example, in some of the sources such as the one invented by Von Ardenne, sputtering and erosion will be very harmful. Proper design must eliminate this or automatic replacement must be designed into the equipment. In the case of a plasma engine it may be difficult to find a source of plasma which will operate over an extended period of time. The instrumentation in the development laboratories must provide much accurate data on these effects so that reliable means can be devised for overcoming them. What has been said concerning the engine itself also applies to the power supply, and the generator, which must likewise be completely trouble-free over long periods of time. The whole mission will be jeopardized if any failure takes place in the power supply, the electric generator, or the engine.

6. ENGINEERING PROBLEMS

A large number of problems are confronted in this type of research, some of which are scientific and others are engineering. It is the purpose of this section to discuss the engineering problems which must be

solved before an electric propulsion engine is developed.

6.1 Loss of Energy by Radiation

The first problem has to do with loss of energy by radiation in the ion type of engine which uses the cesium ions which have been produced by contact with tungsten. The tungsten must be at a temperature from 1200° to $1500^{\circ}K$. As a consequence it radiates an appreciable amount of energy. If it is found that potassium must be used in place of cesium, the temperature must be raised several hundred degrees, and the loss of energy increases as a result. The amount of heat radiated per second is proportional to the forth power of the absolute temperature of the radiating body. The judicious use of reflectors can reduce this loss of heat.

6.2 Sputtering

The second problem which is of great importance is sputtering. In several types of ion sources sputtering takes place. This phenomenon is especially deleterious in that the lost material has no useful function and the sputtering may change the characteristics of the surface on which it takes place. Several types of ion sources are especially susceptible to this type of action. For instance, it is one of the main problems in connection with the bombardment source using the Von Ardenne geometry.

6.3 Corrosion

The third engineering problem deals with corrosion. The alkali metals such as cesium and potassium are very active chemically and unless they are properly handled with materials which are not attacked by them, corrosion can take place. This not only fouls the surfaces—as, for instance, the porous tungsten plug through which the vapor goes—but it can also act on other portions of this engine, greatly reducing the life. Since one of the advantages of electric propulsion is to have the engine operating continuously for periods which may exceed a year, this is a very serious problem.

6.4 Collimation of the Beam

A fourth problem, which is related to sputtering and perhaps to corrosion, is the collimation of the ion beam. If the beam diverges, the sput-

tering becomes far greater. A well-collimated beam is ideal from the standpoint of a foolproof type of engine. A beam of ions can be collimated by the action of an axial magnetic field. Also, an electrostatic field which acts similarly to the electrostatic lens in a cathode-ray tube has applications. Other systems are described in Appendix 6.

6.5 Development of a Propellant Feed

The fifth problem has to do with the development of a suitable propellant feed. The manner in which the propellant is fed to the ion source can be very important both in the ion and plasma engines. It is especially critical in those engines which use cesium ions, and a porous tungsten plug for producing them. If the propellant flow is too large, the ratio of the surface of the tungsten to that in contact with the cesium is not large enough and, therefore, complete ionization does not take place. If the flow is too small there is insufficient thrust. This problem of a suitable propellant feed becomes more critical as the development of a practical engine proceeds. It is estimated that a space ship on a trip to Mars must have an area of the engine exhaust greater than 1 m^2. Even though this square meter is composed of the exhaust from a large number of small engines, the overall problem of a proper feed for the propellant becomes critical. In some cases, the propellant has to be heated to the proper temperature; for instance, alkali materials to be used in the ion engine must be vaporized. In the case of plasma engines, it is essential that the source of the plasma be fed into the engine at the proper rate.

6.6 Selection of the Proper Colloid

The sixth problem is concerned with the colloid type of engine. The selection of a proper colloid will probably determine the success or failure of this scheme. It is especially important from the practical standpoint to develop the colloid engine which can use a large variety of materials. The hope that propellant materials for such an engine can be found on the moon is very real. The use of lunar materials can make a very large difference in the payload of a ship going there and back. It would appear as if some method of mechanically pulverizing suitable

materials should be studied in detail. One of theproblems existing on the earth will not be present on the moon; namely, the compacting of such materials by moisture. There are other problems with colloids aside from the one of using materials which may be present on the moon. The advantage of employing a material at a lower charge-to-mass ratio than exists with ions is great enough to justify a considerable amount of research. If a method can be found for restricting the value of the charge-to-mass ratio within narrow limits, this type of engine will have a distinct advantage in trips to the moon as well as over shorter distances.

Experimenters working in this field differ in one very important detail; namely, whether or not the particles should be insulating or conducting. The engineering procedures will be different in the two cases. Some of the scientists are emphatic in stating that the particles should be conducting, but at least one experimenter believes he has observed that the electrostatic law which states that the charge on a conductor resides on its surface may not be applicable if this conductor is a sphere the radius of which is smaller than a certain critical value. This statement seems reasonable from the viewpoint of modern physics which holds that the charge is not due to the presence or absence of a continuous electrical fluid but rather to whether there exists a superabundance or lack of electrons.

Another consideration in this field is concerned with liquid colloids. The selection of an appropriate liquid as well as the method of spraying it and obtaining uniform size droplets carrying the same charge, is a difficult problem. However, there does not seem to be a necessity for a scientific breakthrough, but rather very thorough engineering research.

6.7 Development of the Power Supply

A seventh engineering problem of major significance has to do with the development of the proper power supply. For some missions it has even been suggested that perhaps a solar collector can be used. This does not seem to be too practical since the amount of solar energy falling upon each square meter is only a little in excess of 1 kw. However,

there has been a good deal of discussion in the various reports about the possibility of using solar energy for an ion engine. By far the most practical and important type of development lies with the Atomic Energy Commission. It seems very probable at the present time that suitable power supplies using the fission reaction will be available within the next five years. As a matter of fact, certain scientists predict that a power supply will be available which may have a weight less than 1, or perhaps 1/10, pound per kilowatt output. The entire future of electric propulsion is dependent upon the development of suitable power supplies. The great advantage of a nuclear power source is that the weight of the fuel is neglibible so that it is only necessary to consider the weight of the propellant and the weight of the power supply itself, together with the weight of the electric engine to utilize it.

Several writers have called attention to the possibilities of a fusion reactor. This type of power supply has tremendous advantages; however, a controlled fusion reaction is still in the future. One disadvantage of the nuclear reactor on a space mission is emission of the harmful radiations which are deleterious to both human beings and certain types of electronic equipment. As a consequence, weight must be wasted on shielding and the power supply cannot be in close proximity to the part of the ship which houses people and sensitive equipment. A fusion power supply would obviate this difficulty since there is practically no harmful radiation from a controlled thermonuclear reaction. Also from an energy standpoint the thermonuclear reaction will give a greater amount of power per gram of fuel used.

6.8 Reduction of Weight

The eight and most important problem is concerned with weight, since all components of this space ship must be boosted into orbit by chemical propulsion. A discussion has already been given above concerning the weight of the power supply. In an overall consideration of weight, it must be emphasized that the development work is not just concerned with the device but with a system in which all parts must function in a very reliable manner. Otherwise, such developments would have very

little practical value. The system must be compatible with the mission and the time taken for the mission is a most important consideration in the determination of the type of engine to be used. The objective of a space mission is not just to place an object in the proper orbit. A space vehicle must carry detecting and measuring equipment and, in many cases, human beings. All of these constitute the payload.

If nuclear energy is used in the power supply, the weight of the nuclear fuel can be neglected. Four weights are important for design considerations, namely,

1. The weight of the power supply,
2. The weight of the propellant,
3. The weight of the payload,
4. The weight of the engine.

The weights are very definitely related to the specific impulse of the engine.

In considering these weights it is important to include with the power supply the weight of the engine. If we adopt the rule of thumb that the specific impulse will be selected so that the weight of the propellant is just equal to the sum of the weight of the power supply plus the engine we arrive at a quantity which is a function of the specific impulse which is proportional to the square root of the weight of the power supply. Now the weight of the propellant is a function of the time of the mission so that these weights are interrelated. The weight of the payload is what is left over. It is the difference between the sum of the other weights, and the weight which can be boosted into orbit. Curves and nomographs have been published to aid design engineers. A special type of nomograph is given in the thesis of Captain Winguerson,[1] pages 11 and 12.

7. NEUTRALIZATION OF THE SPACE CHARGE

7.1 Electron Beam Neutralization

In the case of plasma propulsion, there is no necessity to worry about neutralization of the beam since a plasma is composed of equal numbers of positive and negative charges so that as a whole it is neutral. However, with ion and colloid propulsion this poses a very severe problem. The

ions as they leave the ship form a space charge which repels other ions from being ejected. This space charge must be neutralized in order for the propulsion to exist. There are several means theoretically by which this can be accomplished. The method in most common use is to use an electron beam which originates from a thermionic emitter. The beam of electrons is shot into the beams of ions in such a manner that the two mingle immediately and the electrons then neutralize the positive ions and the space charge. However, with electrons even the thermal velocities are much greater than those of the positive ions and neutralization becomes very difficult. As a matter of fact, there are people working in this field who have stated that neutralization of the space charge with electrons seems to be almost impossible.

7.2 Neutralization by Charge Exchange

A method used by one of the laboratories which uses the Duo-Plasmatron as a source of ions is to obtain beam neutralization by the principle of charge exchange. The fast-moving ions pass through a region in which there are neutral atoms of the same type moving slowly. It is possible for the fast-moving ion to capture an electron from the slow neutral atom leaving it positively charged, but the fast ion is not slowed down in this process and emerges as a fast neutral atom. The slow-moving ion, as a result, drifts over to the walls of the chamber and gives up its charge.

7.3 The PIG Method of Neutralization

Another method for beam neutralization is used in the Penning Ionization Gauge source. A description of this source is given in Sec. 2.3.

7.4 Neutralization by Negative Ions

Of course, if negative ions could be produced efficiently they would form a very good means of neutralizing the beam of positive ions since their velocities are comparable. Also, their masses are comparable so that the net result would not only be neutralization but a beam which would have propulsion possibilities similar to those of the positive ion beam.

Dr. Kash, of Lockheed Aircraft Corporation, has presented a paper in which he proposes to obtain negative ions also by contact ionization. Mr. Hitchcock, of the Air Force Cambridge Research Laboratories, has made a proposal for obtaining negative ions from hydrogen. Mr. Hitchcock's proposal is Appendix 11.

The beam of electrons can be shot into the beam of ions longitudinally. Most of the experimenters working with ion engines propose to do it in this manner. However, there has been some discussion about injecting the beam of electrons at right angles to the beam of ions, and certain advantages are claimed for this method.

Very recently it has been reported by laboratories of the Hughes Aircraft Co. that neutralization of the beam of ions has been accomplished with electrons. A very ingenious method has been used by this company to overcome the disparity in the velocities of thermal electrons as compared with the velocities of ions in the beam. They inject the electrons through orifices in a cylinder surrounding the beam and at right angles to it. The electrons are also in a trap, which does not allow them to overcome the potential barrier of the trap. Time is available for the electron velocities to become randomized. The result is apparently that the ion beam emerges completely neutralized. A great deal of attention is given by this company to the instrumentation. The amount of neutralization is measured by the degree of collimation of the beam. This measurement is made by allowing the beam to impinge upon a segmented target and then measuring the current to each segment of the target. In this manner they are able to detect the divergence or lack of divergence of the beam, even in a very high vacuum.

8. RADIOFREQUENCY INTERFERENCE

This study was undertaken preparatory to an analysis of the radio interference arising from electric propulsion devices. This aspect of electric engines is very important, especially in certain types of engines which are worse than others. From a cursory examination of the problem,

one might conclude that proper shielding could eliminate the deleterious results of the generation of the radiofrequency interference, but only certain types of interference can be eliminated in this manner. On a space mission the signals received by the vehicle will be very weak, and consequently orders of magnitude less in intensity compared with interference which might be generated by an electric engine. As a consequence, communication can fail completely.

One can assume that the ordinary types of interference generated in a high-voltage power supply will be reduced to an acceptable level by proper engineering procedures. However, with ion and colloid propulsion, very high voltages will probably be used and although the vehicle will be in a high vacuum it may pass through regions where breakdown can occur. It is probable that the greatest amount of interference will be generated by plasma oscillations in the exhaust, or oscillations occurring when the beam of ions is not properly neutralized.

Even when there is proper neutralization of the beam of ions, interference may still be generated. Since a neutralized beam of ions is in reality a plasma, it can be expected that plasma oscillations will take place when conditions are ripe for their existence, either in the exhaust of an ion engine properly neutralized or that associated with one of the types of plasma engines.

Conversations with engineers and scientists working with ion engines has indicated that a very large amount of interference can be generated. Unfortunately, interference generated in this manner is not subject to shielding since it occurs in the exhaust of the engine and radiates directly into space. Since communication signals must also travel in a general region of space where the interference is located, there exists a high probability that the engine cannot run during those periods of time when long distance communication is necessary. It is possible to program these communication intervals at definite times. However, emergencies may exist when communication from the earth, or satellites about the earth may be important and it may become very disadvantageous to wait until a programmed time arrives.

This whole problem of interference to communications systems must be studied very carefully during the development stages of electric engines. It is not too early at all to consider the problem and to design equipment and methods for abating the effect.

Appendix 1

DERIVATION OF THE ROCKET EQUATION

The derivation of the rocket equation is as follows:

Let

M_o = initial mass of vehicle and fuel
v = velocity at any instant
C = average velocity of jet with respect to vehicle
m = mass of propellant left at any time

We can then write for the momentum at any time

$$= (M_o - \int dm)v,$$

and after the ejection of mass dm with a velocity C the momentum

$$= (M - \int dm - dm)(v + dv).$$

The vehicle is going to the right and the exhaust stream to the left. The law of conservation of momentum says the total momentum must be the same before and after the ejection of mass dm with a velocity C which is measured with respect to the vehicle.

$$(M_o - \int dm)v$$
$$= (M_o - \int dm - dm)(v + dv) + (v - C)dm,$$

where $(dm)(v - C)$ = momentum of exhaust during time dt.

Removing parentheses,

$$(M_o - \int dm)v = (v - C)dm + (M_o - \int dm)v - vdm + dv(M_o - \int dm),$$

where we neglect dmdv. Cancelling the terms $(M_o - \int dm)v + vdm$, we get

$$C\,dm = dv(M_o - \int dm).$$

It is to be noted that the velocity as measured by a stationary observer is on each side of the equation and consequently can be cancelled, resulting in an equation involving only the velocity relative to the vehicle.

Let

$$\int_o mdm = m.$$

Then

$$Cdm = (M_o - m)dv.$$

This equation states that the increase of momentum of the vehicle is equal to the momentum of the jet, all measured during the time dt.

This equation can readily be integrated

$$\int_{0}^{M_p} \frac{C\,dm}{M_o - m} = \int_{v_o}^{v_v} dv,$$

or,

$$C \ln (M_o - m) \Big]_{o}^{M_p} = v - v_o = \Delta v$$

$$-C \ln (M_o - M_p) + C \ln M_o = v$$

or

$$C \ln \left(\frac{M_o}{M_o - M_p} \right) = \Delta v = v - v_o$$

$$C \ln \frac{1}{1 - \frac{M_p}{M}} = \Delta v \; ;$$

Δv is the same when measured by either a fixed or moving observer.

Appendix 2
THE CESIUM ION SOURCE

The starting point in the discussions of the Cesium Ion Source is the Saha-Langmuir equation

$$\frac{n_+}{n_a} = \frac{1 - r}{1 - r_a}\,\frac{1}{2}\,e^{\left[\frac{\epsilon(\Phi - I)}{kT}\right]}$$

where r and r_a are the reflection coefficients for ions and atoms, Φ is the thermionic work function, I is the ionization potential of the cesium atom and ϵ is the charge on the electron. S. Datz and H. Taylor[2] have modified this equation to give the probability that an incident atom leaves the surface as an ion so that

$$\frac{n_+}{n_a} = (1 - r_i)\;1 + \frac{1}{2}\,\frac{(1 - r_a)}{(1 - r)}\left[\exp\left(\frac{-\,\epsilon(\Phi - I)}{kT}\right)\right] - 1\,;$$

r_i is not necessarily the same as r_a since the beam atoms are not at filament temperature. Figure 2.1 taken from this paper gives the ionization efficiency of potassium on oxygenated tungsten; Fig. 2.2 that of cesium, rubidium and potassium on pure tungsten. The high efficiency of the tungsten-oxygen-potassium combination is due to the fact that oxygenated tungsten has a work function of 6.24 v so that the difference between this value and the ionization potential of potassium (5.138 v) is sufficient to raise the ionization efficiency to almost 100 percent if the temperature is high enough to prevent the condensation of the metal on the filament. If the cesium condenses on the emitter, then the work function corresponds to that of cesium and it does not function as a contact ionizer. On the other hand the temperature must not be so high that the emitter functions as a thermionic cathode with the corresponding emission of electrons, since this action also destroys the fundamental phenomenon which causes contact ionization. Moreover, the flow rate

must not be sufficiently high to cause a collection of the cesium on the emitter with a resulting reduction of the ionizing efficiency. A value of one percent* for the ratio of the surface of tungsten covered by cesium to the whole surface has been stated.

There is a temperature called the critical temperature at which the ion current changes by an order of magnitude. An empirical equation gives the current density j in terms of the critical temperature T_c. This equation is $\log_{10} j = 11.993 - 14350/T_c$ in ma/cm^2. A curve showing the cesium ion current at the critical temperature is shown in Fig. 2.3 taken from a General Electric paper by G. Kuskevics,[3] entitled Ion Rocket Efficiency Studies.

*See thesis by Ed L. Battle, B.S. A.E., Captain, USAF, and Frederick E. Davis, Captain, USAF, presented to the Faculty of the School of Engineering of the Institute of Technology (Air University), United States Air Force, July 1960, page 6.

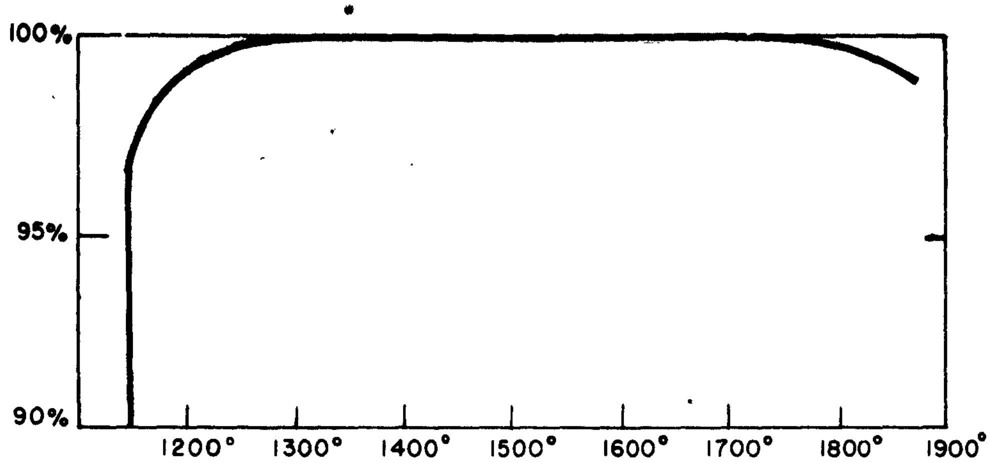


FIG. 2.1. Ionization of potassium on oxygenated tungsten.

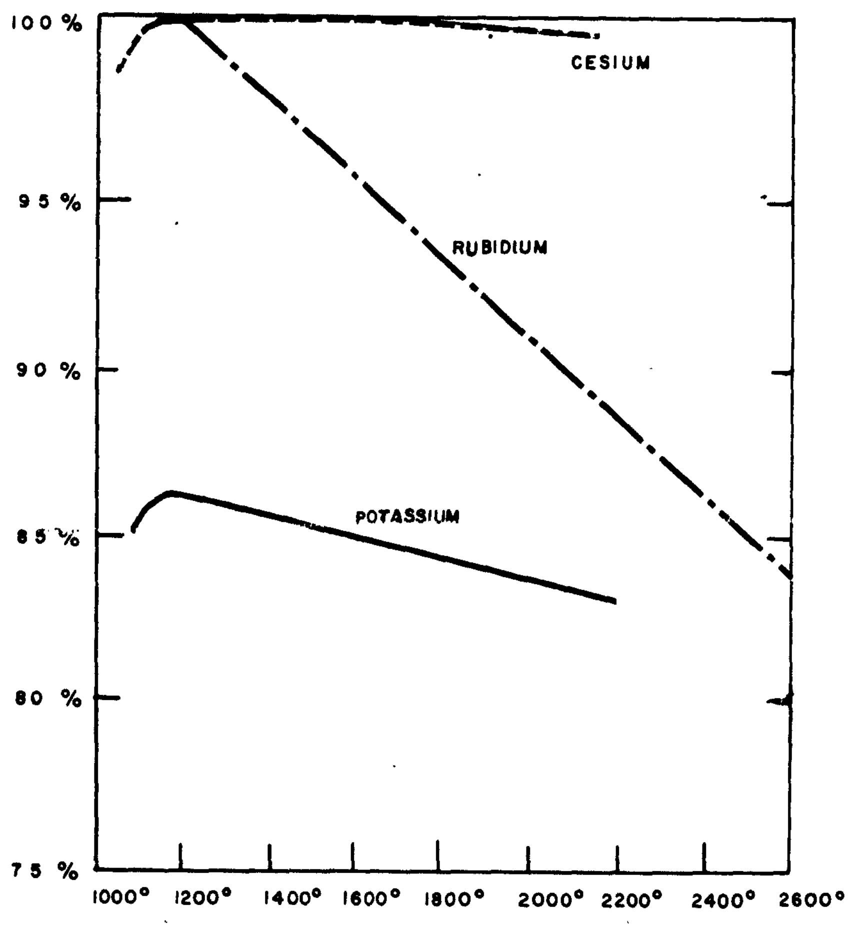


FIG. 2.2. Ionization of cesium, rubidium, and potassium on pure tungsten.

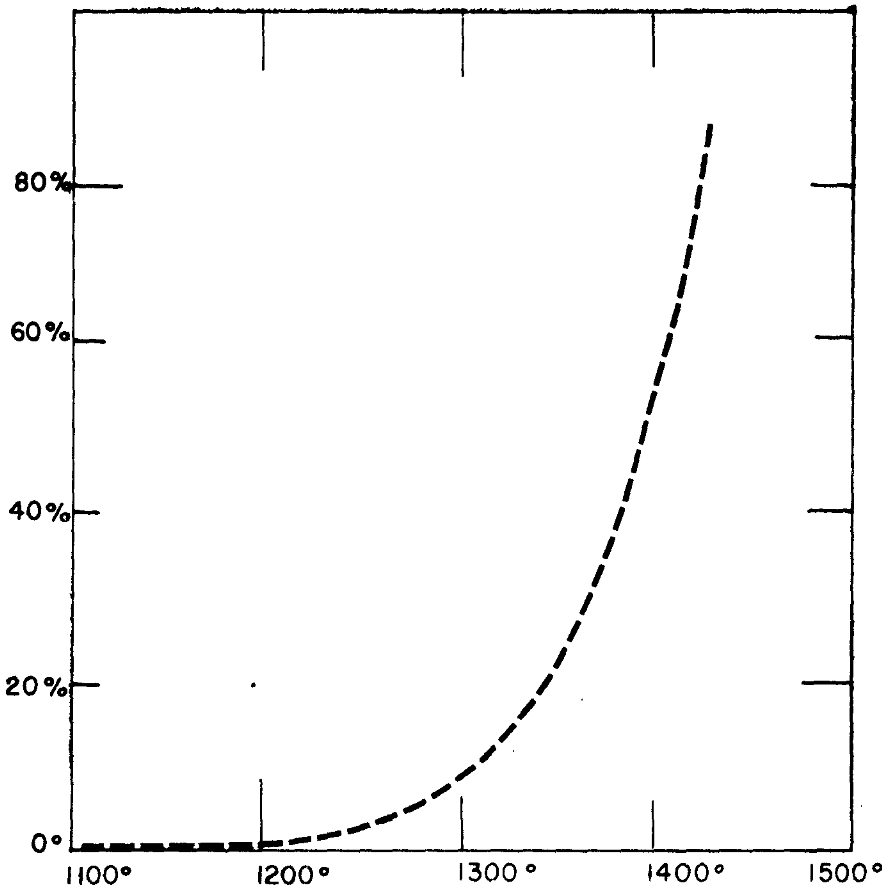
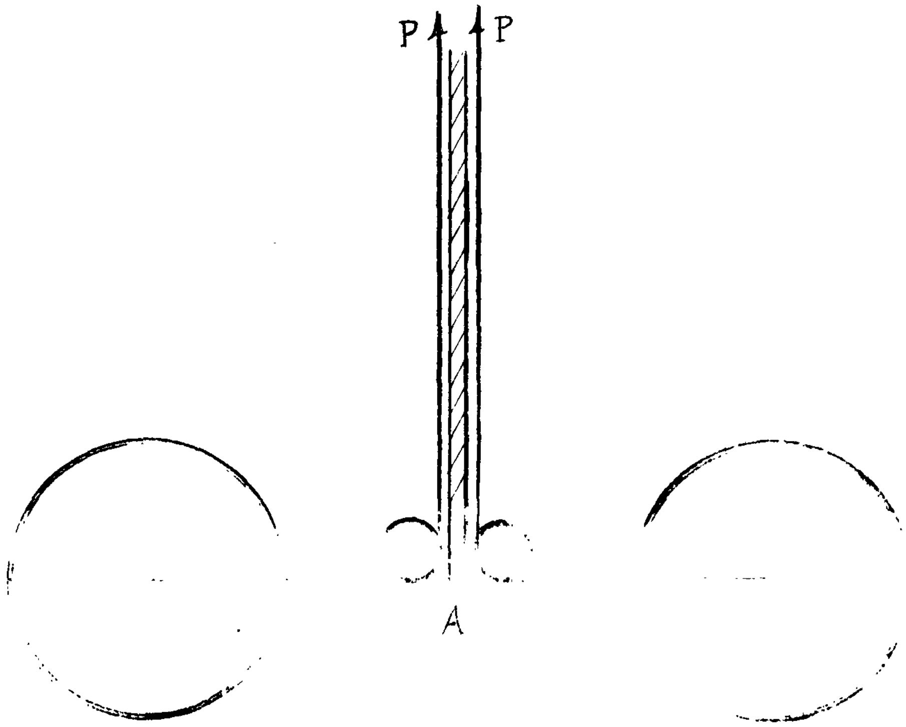


FIG. 2.3. Cesium ion current at the critical temperature.

Appendix 3

REFLECTION OF IONS BY A MAGNETIC FIELD GRADIENT

Discussion of the Physics of the reflection of a moving ion in going to a stronger magnetic field. Consider the lecture demonstration apparatus as shown in the accompanying sketch.



Two balls of mass m each are rotating about a vertical shaft A with an angular velocity ω. They are attached to two cords p which can be pulled causing the balls to come closer together. The angular velocity increases, since the product $mR^2\omega$ must remain the same. Suppose the new distance is R. Work has been done on each ball to reduce the distance between them. This work on each ball

$$= -\int_{R_o}^{R} \frac{mv^2}{R} dR = -\int_{R_o}^{R} mR\omega^2 dR$$

$$W = -m\int_{R_o}^{R} \omega^2 R dR = -m\omega^2 \int_{R_o}^{R} R dR$$

$$= -\frac{m\omega^2}{2}(R^2 - R_o^2) = \frac{m\omega^2}{2}(R_o^2 - R^2).$$

Therefore, the work is equal to just the difference in the kinetic energy of rotation in the two conditions. Now if instead of a force 2p doing an amount of work resulting in an increase in the kinetic energy of rotation, the cords 2p are attached to a mass that had a certain amount of kinetic energy of translation. If conditions should cause an additional force to be exerted along 2p the work done would slow down the mass moving linearly and could even result in stopping such linear motion.

The motion of a charged particle around a line of magnetic force is just exactly this case. The centripetal force* ($mv^2/R = Hqv$) increases with H. The energy comes from the kinetic energy of translation along the line of force and may stop the translational motion in that direction if H increases toward the right. The charge is therefore, under these conditions reflected by an increasingly intense magnetic field.

Suppose the magnetic field is in the x direction. The angle which the velocity of the ion makes with the x axis is very important in determining whether or not the charge is reflected by the magnetic field. Let this angle be θ as shown in the figure.

In Appendix 8 it is shown that the magnetic moment of a charge rotating about a line of force $= 1/2\ mv_{\perp}^2/B$ where v is the velocity perpendicular to the magnetic field. Let $v_{\parallel}$ be the component of the velocity

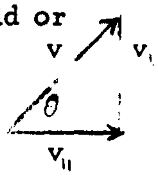
---

*The equation $mv^2/R = Hqv$

or $mR\omega^2 = HqR\omega$.

$\omega = 2\pi f = Hq/m$ and f is proportional to H.

parallel to the magnetic field or



and consider two places where the magnetic field has the values B_o and B. Since $1/2\ mv_\perp/B$ must remain the same

$$\frac{v_{o\perp}^2}{B_o} = \frac{v_\perp^2}{B} \text{ or } \frac{v^2 \sin^2\theta_o}{B_o} = \frac{v^2 \sin^2\theta}{B}$$

from which

$$\sin^2\theta = \frac{B \sin^2\theta_o}{B_o} \text{ if } \frac{B \sin^2\theta}{B_o} = 1\,,$$

then $\theta = 90^\circ$ and there is no translation.

In other words the charge is reflected. It is evident therefore that whether or not the charge is reflected depends upon the angle it makes with the field and the ratio of the intensities of the field. In going from a weak magnetic field to a stronger one, if θ is greater than a critical value it will be reflected. If less than this critical value it will go through. We have

$$\sin\theta_c = \frac{\sqrt{B_o}}{B}$$

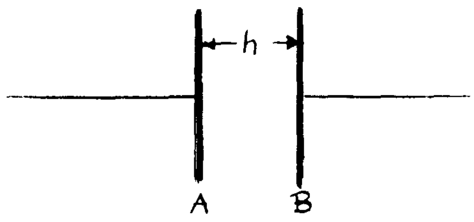
and θ_c is this critical angle. If the particle goes into a very strong field B, in comparison to that from which it came, it can have a smaller angle with the magnetic field and still be reflected.

Appendix 4

DERIVATION OF THE ENERGY DENSITY EQUATIONS

The following proofs, although not general, illustrate the expression for the energy density in an electrostatic or a magnetic field. The cgs system of units is used.

Case No. 1 Electrostatic Field



Consider a parallel plate capacitor with distance between the plates = h. Calculate the work done against the field in taking a charge dq from plate A to B. Assume there is already a field of E volts/cm existing.

The work

$$dw = E\,dq\,h \text{ or}$$
$$w = hq\int_0^q dqE$$
$$= hq\int_0^q E\,dq$$

Now Eh = the number of volts between A and B and since this is a capacitor in an electric circuit

Q = (Eh) C where C = the capacity of the condenser = $KA/4\pi h$ = $EKA/4\pi$

$$w = \frac{hAK}{4\pi}\int_0^E E\,dE \text{ since } dq = \frac{KAdE}{4\pi}.$$

The work = $\frac{hAKE^2}{8\pi}$, and since hA = volume between the two plates we have energy density = the work to charge = $KE^2/8\pi$.
In a vacuum K = 1, energy density = $E^2/8\pi$ ergs/cm^3.

Case No. 2 The Magnetic Field

Consider a coil of inductance L in an electric circuit. The emf = $L\frac{di}{dt}$, the total energy in the field of the coil carrying a current

$$I = \int_0^I \frac{Ldi\ idt}{dt} = \int_0^I L\,i\,di = \frac{1}{2}LI^2.$$

The inductance of a long solenoid of length h is

$$L = 4\pi\mu mn^2 hA \quad \text{also} \quad H = \frac{4\pi nI}{h}$$

and

$$I = \frac{Hh}{4\pi n}$$

substituting in the expression for $1/2\ LI^2$

$$\frac{1}{2}LI^2 = \frac{4\pi\mu hn^2}{2h}\ \frac{h^2H^2}{16\pi^2n^2} = \frac{4\pi\mu n^2H^2h^2}{2h(16\pi^2\pi^2)}$$

which reduce to

$$\frac{1}{2}LI^2 = \frac{\mu hAH^2}{8\pi} = \text{total magnetic energy} = \text{energy} \times \text{volume}.$$

Since hA = volume of inside of coil, $\mu H^2/8\pi$ = energy density of the magnetic field in ergs/cm^3. In air μ = 1 and the energy density of a magnetic field in air is

$$\frac{H^2}{8\pi}\ \frac{\text{ergs}}{\text{cc}}.$$

It is interesting to note that either an electric or magnetic field exerts pressure which in dynes/cm^2 is equal to the energy density in ergs/cm^3. This can be seen as follows: A working substance is enclosed that exerts a pressure p. An amount of heat ΔQ is added that will cause the piston to rise doing an amount of work = $p\Delta v$. The heat ΔQ is equal

to the increase in internal energy or

$$\Delta Q = \Delta(Ev) = v\,\Delta E + E\,\Delta v$$

$$p\Delta v = v\Delta E + \Delta v$$

or

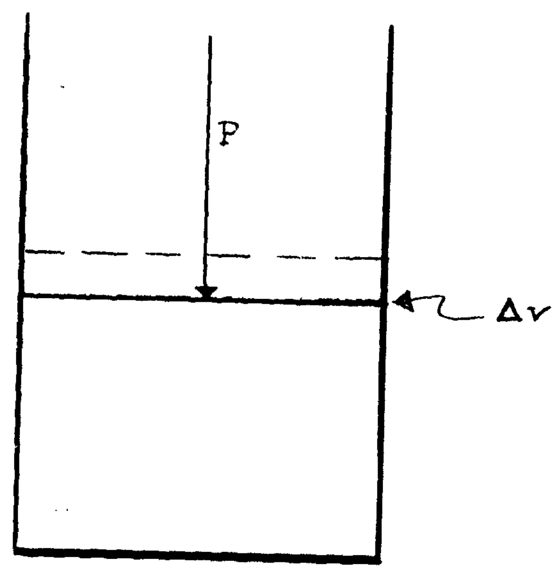
$$P = v\Delta E/\Delta v + E = v\,\Delta E/\Delta v + E$$

now electric or magnetic energy density is independent of the volume; that is

$$\frac{\Delta E}{\Delta v} = 0 .$$

Therefore, $p = E$ or the pressure in dynes/cm^2 = energy density in ergs/cm^3

$$p = E$$



Appendix 5
CHILD'S LAW AND THRUST IN ION ENGINE

This law plays such an important role in ion propulsion that the derivation seems justified. Three starting equations

1. Poisson's equation in one dimension

$$\frac{d^2V}{dx^2} = -4\pi\rho$$

2. The energy equation

$$\frac{mv^2}{2} = Vq \quad \text{or} \quad v = \sqrt{\frac{2qV}{m}}$$

3. The continuity equation

$$J = nqv.$$

From Eqs. (2) and (3)

$$J = nq\sqrt{\frac{2qV}{m}}$$

and this placed in equation

$$\frac{d^2V}{dx^2} = -\frac{4\pi J\sqrt{m}}{\sqrt{2qV}}.$$

Let

$$\frac{dV}{dx} = \rho, \text{ then } \frac{d^2V}{dx^2} = \rho\frac{d\rho}{dV}$$

$$\rho d\rho = -4\pi J\sqrt{\frac{m}{2q}}\frac{dV}{V^{1/2}}$$

$$\frac{\rho^2}{2} = 4p\sqrt{\frac{m}{2q}}\;V^{1/2}\;x2x$$

$$\rho = 4\sqrt{\pi J}\;4\sqrt{\frac{m}{2q}}\;V^{1/4} = \frac{dv}{dx}$$

$$\int \frac{dV}{V^{1/4}} = \sqrt[4]{\pi J}\ \sqrt[4]{\frac{m}{2q}}\, dx$$

$$\frac{4}{3} V^{2/4} = \sqrt[4]{\pi J}\ \sqrt[4]{\frac{m}{2q}}\, x$$

$$\frac{1}{9} V^{3/2} = J\pi \sqrt{\frac{m}{2q}}\ x^2$$

$$J = \frac{1}{9\pi} \cdot \sqrt{\frac{2q}{m}} \cdot \frac{V^{3/2}}{x^2}$$

Now the thrust per unit area

$$\frac{F}{A} = Ms = \frac{Jmv}{q}$$

$$= \frac{1}{9\pi}\sqrt{\frac{2q}{m}}\ \frac{m}{q} \cdot \sqrt{\frac{2qV}{m}} \cdot \frac{V^{3/2}}{x^2}$$

$$= \frac{2}{9\pi}\ \frac{V^2}{x^2}$$

$V/x =$ Electrostatic field strength.

The force = thrust varies as the square of the field strength but the exhaust velocity and specific impulse depend only upon the voltage difference V.

Appendix 6

GEOMETRIC CONFIGURATIONS OF ELECTRODES TO FOCUS ION BEAMS

In the case of the ion engine many of the writers describing such work mention the Pierce Geometry.* This was first given in a paper by Pierce in the Journal of Applied Physics, Volume 11, 548-554, 1940, but it is better for the reader who wishes to follow the subject further to read a book by Pierce entitled Theory and Design of Electron Beams, 1949, D. Van Nostrand Company Inc., New York.

Of interest to ion propulsion engineers is that part of the book starting with Chapter 10, and especially Figs. 10.5 and 10.6. Also, Dr. Pierce discusses the use of an electrolytic tank. In the study of electrostatic field configurations, this is a common device used by vacuum tube engineers. Large electrolytic tanks of this type are being employed at the Hughes Aircraft Company, and Rocketdyne. The tanks in use at these two companies differ materially from the simple ones used to map fields in the Elementary Physics Laboratory. In these tanks one is not

*

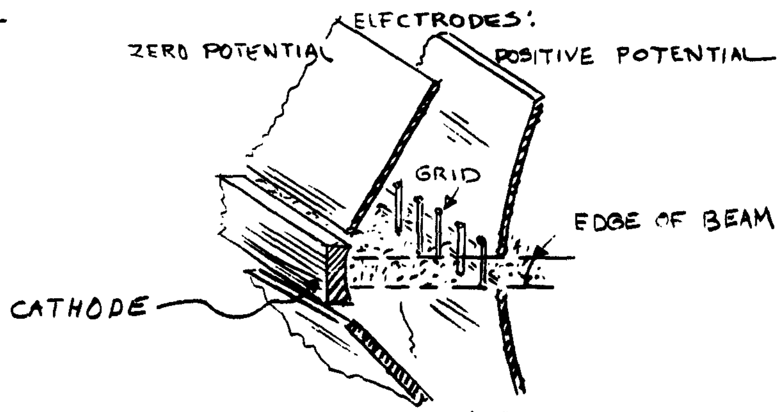


FIGURE 6.1

The essential feature of this technique is to shape the accelerator electrodes so as to counterbalance a mutual repulsion of the space charge at right angles to the direction of motion. If such a Geometry is used in the initial acceleration of the ions, it is possible to maintain a sharp boundary between the charged beam, and the surrounding space which is charge free. Figure 1 taken from Pierce's paper illustrates this method of shaping the electrodes.

limited to two-dimensional analysis, but a fair amount of three-dimensional analysis can be made. Also, the tanks can be modified to show the effect of space charge.

The proper design of an electrode system is extremely important in that it is possible by this means to materially reduce the effect of sputtering.

An entirely different attack on the problem of an ion engine is given by Dr. Childs in a paper at the AFOSR Symposium on Advanced Propulsion Concepts, October 7-9, 1959 in Boston. In this paper Dr. Childs uses the analogy to a screen grid thermionic tube. He proposes a grid accelerator and a method of replacing the material that is eroded from it by sputtering. He notes that it may be necessary to use tungsten grid wires to keep the eroded material from coming in contact with the tungsten emitter and if true, it becomes especially difficult to replenish the outside coating of the wires. However, he recommends that it is desirable to continue the development of grid electric ion engines.

Other types of electrostatic lenses are used in designs in other company laboratories. For instance, at the High Voltage Engineering Company in connection with the Duoplasmatron source a so called Einzel lens is used.

The most common use of electrostatic lenses is in the focusing of the beams in cathode ray tubes, and a great mass of information is available.

A thorough discussion of the design techniques for ion engines is given in Rocketdyne report dated 12 February, 1959 by Mr. S. L. Eilenberg.[5]

Appendix 7

COMPARISON OF THE RAIL TYPE OF ACCELERATOR WITH AND WITHOUT AN EXTERNAL MAGNETIC FIELD

In the diagram is represented the rail type of accelerator and the radius of the cylindrical rails is labeled R_o. The distance between the rails is called $2 \times R$. An approximate method of calculating the force on the conductor AB is to consider it as a wire carrying a current in the magnetic field of the remainder of the circuit of which only the portion close to AB is important

Consider the magnetic field between the points AB due to the remainder of the circuit as one half that which is calculated as a magnetic field close to an infinite wire carrying the same current This expression is equal to $2I/y$ The force measured in dynes on the wire carrying I amperes (emu) is equal to $F = H \times I L$ where L is equal to the length of the wire in the magnetic field Substitutions into this equation will obtain the value

$$FH = I\int_o^H Hdy = 2I\int_{R_o}^{R} I\,\frac{dy}{y}$$

and

$$F = 2I^2(\ln R - \ln R_o) = 2I^2 \ln\frac{R}{R_o} .$$

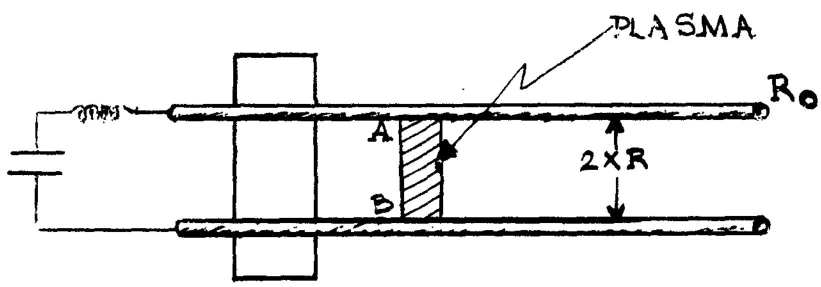


FIG. 7.1 Rail-type motor showing the magnetic field is perpendicular to the paper.

Now, compare this with the force on the same wire with an external magnetic field in a direction perpendicular to the paper and such as to push the wire to the right. The expression is F = HIL where in this case H is equal to the strength of the magnetic field; L has the value 2R as before.

If we now take the ratio of the force in the first case to the force with an external magnetic field, we obtain

$$\frac{F_1}{F_2} = \frac{2I \ln \frac{R}{R_o}}{2R} = \frac{I \ln \frac{R}{R_o}}{RH}$$

The limit for a practical external magnetic field is 10^4 gauss. If we assume that the wires are 10 cm apart so the R equals 5 cm and that the radius of each wire is 1/10 of a centimeter, the ratio of R to R_o is 50. The natural logarithm of this ratio is 3.92.

Let us substitute the following values in the above equation:

$I = 10^4$ abamp $= 10^5$ amp
$H = 10^4$ gauss
$R = 5$ cm.

After substitution it can be seen that the force is 3.92/5, or 0.78 times as great as if an external magnetic field is used. Of course, if an external magnetic field is used we also get the force which is obtained by the conductor AB being in the magnetic field of the rest of the circuit. However, this calculation shows that the contribution of the force due to the external magnetic field becomes less and less important as the currents increase beyond 100,000 amperes (10,000 emu ampere). A magnet to give a field of 10^4 gauss over such a wide area would be extremely heavy so that it would be impractical to use under these conditions. The so-called J × B type of engine is therefore not practical under these conditions and only becomes important if comparatively small currents, that is less than 10,000 amperes, are used.

Appendix 8
MAGNETIC MOMENTS

Consider a bar magnet of length l between poles P, in a uniform magnetic field as shown in the figure.

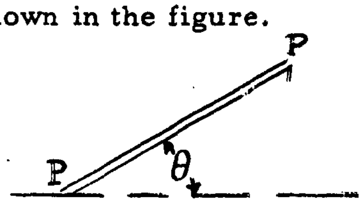


FIGURE 8. 1

The force on the poles is PH and - PH and the torque due to this couple is

$$\text{Torques} = (Pl \sin \theta)H.$$

The maximum value of this torque, is for a unit field, = Pl and this value is defined as the magnetic moment of the magnet.

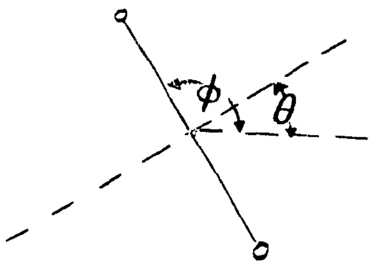


FIGURE 8. 2

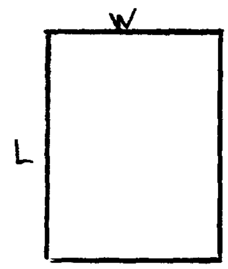


FIGURE 8. 3

A coil carrying an electric current is equivalent to a magnet. Consider the coil shown in the figures with one turn. The force on each wire is HIL sin ϕ.

The torque is therefore

$$\text{Torque} = HIw \sin \phi l$$
$$= HI(\sin \phi)A \quad (A = \text{area of loop})$$

Maximum torque = HIA and for unit field is IA. This quantity is analogous to the magnet case. The magnetic momentum IA = maximum torque in unit field.

If a charge is rotating in a magnetic field of strength H and in a plane perpendicular to the field, we can write

$$mR\omega^2 = H\dot{e}R\omega$$

or

$$m\omega = He$$

$$\omega = \frac{He}{m} = 2\pi f \cdot$$

The magnetic moment

$$= IA = (fe)(\pi R^2) = \frac{He}{2\pi m} e\pi R^2$$

$$= \frac{He^2}{2m} R^2 = \frac{1}{2} \frac{m}{H} \frac{e^2H^2R^2}{m^2}$$

$$= \frac{1}{2} \frac{m}{H} v^2 \quad \text{where} \quad v = R\omega.$$

In some studies it is important to know the radius of the helix in which the ion is revolving. From the equation

$$v = R\omega$$

and

$$= \frac{Bq}{m}$$

we obtain

$$R = \frac{vm}{Bq}.$$

If the ion has obtained its velocity v in falling through a difference of potential V

$$v = \sqrt{\frac{2Vq}{m}}$$

and we obtain

$$R = \frac{1.42}{B} \sqrt{\frac{Vm}{q}} \quad .$$

R is related to the magnetic deflection as follows:

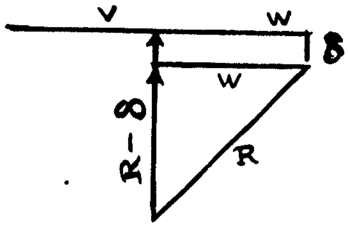


FIGURE 8.4

$$(R-\delta)^2 + w^2 = R^2$$

$$R^2 - 2R\delta + \delta^2 + w^2 = R^2$$

neglect δ^2

$$2R\delta = w^2$$

$$R = \frac{w^2}{2\delta}$$

δ is the deflection of the beam.

Appendix 9

DERIVATION OF THE EXPRESSION FOR THE DEBYE SHIELDING LENGTH

In the discussions involving plasma propulsion there occurs the term which is used many times, namely, the Debye Shielding Length. It was originally used by Debye, a famous German scientist, in connection with a theory which he proposed to explain certain electrolytic phenomena. However, physicists have found the concept very useful in other applications where electric charges are involved. A derivation for this expression follows:

Consider a thin slab-like portion of the plasma of half-thickness—x.

Potential difference from center to the outside obeys Poisson's Equation

$$\frac{\partial^2 V}{\partial x^2} = 4\pi ne$$

or, potential difference

$$= \Delta V = 2\pi nex^2 .$$

The change in potential energy $= e\Delta V$

$$= 2\pi ne^2 x^2 .$$

Let $x = h$ where the change in potential energy equals the kinetic energy

$$\frac{1}{2} kT = 2\pi ne^2 h^2$$

or

$$h = \sqrt{\frac{kT}{4\pi ne^2}} .$$

The quantity h has been named the Debye Shielding Length.

Appendix 10
RADIOFREQUENCY ACCELERATION OF A PLASMA

In the RCA Laboratories located at Princeton, New Jersey, there is an electric propulsion project which differs considerably from any of the others in the country. In this project a nonhomogeneous radio frequency electric field accelerates the charges in a plasma. This acceleration is determined by three factors, the first and most important of which is the gradient of the electric field. However, there are two other forces that produce an acceleration, one of these being the induced electric field and the other collision forces that are analogous to friction. The mathematics that describes the phenomenon is very complicated and makes use of a differential equation due to Mathieu. However, the unique feature of this project is concerned with the fact that it is possible to obtain an acceleration of the ion and electrons in a plasma by means of a time-varying and nonuniform electric field. It is comparatively easy to show that this is possible if instead of considering a sinusoidal wave one assumes a square wave with a period equal to 2 τ. In this derivation it is assumed that there is an electric accelerating field which exerts a force on a charge equal to the product of the charge by the average value of this field and that this force acts for a time equal to τ at the end of which time the direction of motion is immediately reversed for a time equal to τ. During these times the force essentially remains constant except for the fact that the electric field changes a small amount determined by the field gradient. The equations described in this phenomenon were as follows:

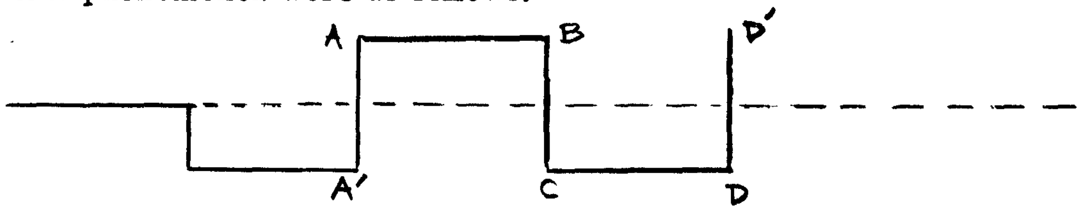


FIGURE 10.1

At

$$A, \rightarrow \vec{E};$$

$$B, \rightarrow \vec{E} + \frac{\partial \vec{E}\, \Delta x}{\Delta x};$$

$$C, \overleftarrow{E} + \frac{\partial \overleftarrow{E} \Delta x}{\partial x} \quad ;$$

$$D, \overleftarrow{E} + \frac{\partial E \Delta x}{\partial x} + \frac{\partial}{\partial x}\left(\overleftarrow{E} + \frac{\partial \overleftarrow{E} \Delta v}{\partial x} + \frac{\partial \overleftarrow{E} \overleftarrow{\Delta v}}{\partial x}\right)$$

$$\text{net} = \sum = \frac{1}{2}\, \frac{\partial E \Delta x}{\partial x} = \frac{1}{2}\, \frac{\partial E \Delta x}{\partial x} \tag{1}$$

Since the product $\partial \overleftarrow{E} \overleftarrow{\Delta x}/\partial x$ is plus and = net drift force,

$$\frac{q}{m}\, \frac{\partial E \Delta x}{\partial x} = \text{net drift acceleration.} \tag{2}$$

Now, if a = acceleration for time τ,

$$\Delta x = \frac{1}{2}\, a \tau^2$$

$$= \frac{1}{2}\, \frac{Eq}{m} \tau^2 .$$

The net drift acceleration is

$$= \frac{1}{4} E\, \frac{\partial E}{\partial x}\, \frac{q\, \tau}{m}^{\;2}$$

$$= \frac{1}{4}\, \frac{\partial}{\partial x}\, \frac{(E^2)}{(2)}\, \frac{q^2 \tau^2}{m^2} . \tag{3}$$

The direction of the net acceleration is determined by the gradient of the square of the electric field. This might be called a drift acceleration, and is represented by Eq. (3).

It is to be noted that all important quantities in this equation occur as squares, so that even though they may be vectors they do not determine a direction. For the same reason, the drift acceleration is independent of the sign of the charge. Therefore, electrons and positive ions have a net acceleration in the same direction.

As the force in mechanics is usually proportional to the gradient of the energy density, and the energy density in an electrostatic field is proportional to the square of its intensity, it can be readily seen why the charges are accelerated by the gradient of the square of this field.

The direction given so far is for single charges. When, however, charges exist in association with many others, as in a plasma, complications arise, and the frictional force and the induced field under certain circumstances can override the drift acceleration given in Eq. (3) above. A detailed mathematical derivation indicates that the direction of the drift acceleration is determined by the relation between the frequency of the applied field and the so-called plasma frequency. The direction of the drift acceleration is reversed when the frequency of the applied field increases from below the plasma frequency to above it.

This method of acceleration is very ingenious, but the acceleration is also very small since it is not proportional to an applied field but to the gradient of the square of this field. Nevertheless, it is conceivable that this principle might be used in a practical engine of the plasma type. It has the advantage that it deals with electric fields but does not require heavy equipment as is the case where magnets are involved.

In these experiments a mercury plasma is used and the frequency is approximately 140 Mcps. Also, the velocity attained by the plasma is in the neighborhood of 2.5×10^6 cm/sec. It is to be emphasized that the charges are accelerated in a nonuniform electrostatic field.

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Appendix 11

PROPOSAL FOR HYDROGEN ION SOURCE

by

W. J. Hitchcock

This is to propose experimental work on a source of quite dense streams of either negative or positive hydrogen ions. These ions can be of any isotope of hydrogen. Likely the source would have longer life than present types and be less damaged by sputtering.

ABSTRACT

Hydrogen ions, from molecular hydrogen within palladium tubes, have been pulled off the surface of the warmed tube by high electric fields after passing through the palladium. As this is analogous to the field emission of electrons, which gives the densest electron streams known, really high fields should give dense streams of ions. Some hydrogen will always pass through as ions but recombine on the surface to molecular hydrogen before it can be pulled off as ions. Electrical breakdown in this hydrogen has not been avoided up to now. Measures can be taken to avoid this electrical breakdown if the voltage gradient is chiefly radio frequency and sufficiently great. There is need for experimental work with alternating current so that limits may be set to what is possible with this type of ion source.

INTRODUCTION: HISTORY

The first palladium ion emission experiments were done in 1938. Translations of these articles are available. Several milliamperes were drawn using 800 v dc and an unknown voltage gradient. There was some disagreement about these results: Did the ions really come from the palladium surface, or were they due to some unnoticed break-

down in the gas? This seems to have been settled by Silberg.[2] He drew very small currents at 5 v, but proved with a mass spectrograph that hydrogen ions were present. His article contains a bibliography.

Various people[3] have drawn ions from tungsten points in the fashion of the field emission microscope. These ions were adsorbed on the tungsten point as molecules from a surrounding gas and then pulled off as ions by the field. Since the gas pressure must be low to avoid electrical breakdown with dc fields, the supply of ions is very limited. The current is almost zero.

Very great, but momentary, hydrogen ion currents have been produced in hydrogen fusion experiments. One procedure is to dissolve large quantities of hydrogen in such metals as palladium or titanium and then draw such an intense electrical discharge that the surface of the metal is ripped off together with the hydrogen it contains. Several reports of this sort have been seen but only one seems to be at hand.[4,10]

Lately, a patent[5] has suggested using high voltage gradients on palladium or nickel points through which hydrogen is passing to get streams of hydrogen ions. A copy of the thesis on which this patent is based is available. The procedure in this proposal is similar except a small dc voltage would be superimposed on a high alternating current. This is very important.

Negative hydrogen ion sources of the von Ardenne type have been used successfully by the High Voltage Engineering Co. to supply the current for their tandem machines. It is rumored that Peter Rose of that company has very recently made some major improvements in this regard, although publication is lacking regarding details. There is a vast amount of literature on the von Ardenne source in general. Its defects are well known: the densest ion streams I know of from it are about 60 amperes per square centimeter.

Most of what is known of hydrogen and palladium is reviewed in Dr. Dushman's book on Vacuum Technique. A notable recent article[6] says the root mean square displacement of the protons relative to the palladium sublattice at room temperature is 0.22 Angstroms. Amongst

other things, Dushman's book mentions the cracking of the palladium with time. This effect is avoidable at moderate temperatures. Then there are effects due to impurities, such as silver. The palladium should be soldered to some relatively massive silver or copper tube which brings the hydrogen up to the palladium and conducts the heat away. A careful reading of the literature makes one wonder if apparently minor details of soldering technique have been the cause of some reported discrepancies. Silver solders, except Sil-Phos, usually give mysterious troubles in high vacuum.

If the area of the ion source is sufficiently small, similar to a dent in a palladium foil soldered over a hole in a silver tube, sputtering difficulties with this ion source can be avoided. This statement is based on the experience of the writer in sputtering researches conducted in the General Electric Research Laboratory more than thirty years ago. Also, his experience with thermionic tubes utilizing small anodes[7] and cesiated cathodes showed that positive ions generated in this manner came from a small volume and could be caught on a grid composed of slats rather than on the cathode.

In a purely electrostatic field, when using this ion source as a source of negative ions, any positive ions that might be formed between the focussing electrodes, would travel in exactly the reverse direction to the motion of the negative ion. This is not true if a suitable magnetic field is used as part of the arrangement for focusing the ions into a beam. Due to the small size of the source of ions, it would be easy to contrive that protons would miss it. It might then be possible to slow them down to where they would do no damage.

PROPOSAL

Electrical breakdown in gases has been studied for many years; the conditions under which there is no electrical breakdown at high voltage gradients and high frequencies have only recently attracted the attention of investigators.[8] It appears that with clean metal parts and with

high voltage gradients attained in a sufficiently short time, there may be a range of frequencies, electrode spacings, and gas pressures at which electrical breakdown does not occur. The procedure proposed here will utilize one electrode of palladium through which hydrogen is passing. At spacings of the order of magnitude of a centimeter the frequency needed would approximate 10 megacycles. The only limit to the voltage gradient which might be used is that which would physically destroy the surface of the palladium. Such fields would not be necessary since there is strong evidence that palladium hydride holds palladium more firmly than hydrogen.

The technical difficulties seem of not much consequence. The use of a purely alternating current voltage is impossible for this would merely jiggle the ions back and forth without getting them permanently away from the surface. A small amount of dc voltage would have to be used in addition.

Electrons evaporating from a surface cool it, but it is possible to have the emission of electrons so intense that the current flowing through a small tungsten point could melt it by the joule heating. Something analogous would happen were the flow hydrogen ions instead of electrons. No doubt the heating would depend on what fraction of the hydrogen came off as ions and what fraction recombined on the surface to form molecular hydrogen. A great deal of theoretical work has been published relative to this phenomenon.[9]

CONCLUSIONS

It is desirable that sufficient investigations be made on this particular ion source to determine the limits of its usefulness. In this regard, it must be realized that there are many applications of an ion source in addition to the neutralization of a beam of positive cesium ions with a corresponding beam of negative hydrogen or deuterium ions.

The use of an ion source is not confined to purely engineering applications. It can play an important role in purely scientific experiments such as charge exchange experiments in hydrogen. It can also make possible the development of an ultraviolet lamp to generate continuous radiation in a vacuum for photo chemical experiments. One simple way to accomplish this objective would be to utilize the cyclotron radiation resulting from the interaction of a beam of positive ions with a corresponding beam of negative ions. It would be advantageous to use beams with high current densities, perhaps in excess of 60 amp/cm^2.

Finally, the writer would like to mention, in connection with ion propulsion, that apparently no one has investigated the possibility of field emission of heavy positive ions which are produced from those metals in which the individual atoms are rather large and have a loosely bound electron. Field emission techniques similar to those used by Dr. Mueller in his microscope might be used, especially if the cathode were shaped in such a manner as to avoid the field emission of electrons. Such an ion engine would use multiple ion beams in a manner similar to the types of cesium ion engines proposed for space vehicles.

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ADDENDUM

At a meeting on Ion Propulsion held at Beverly Hills, Calif. on 24 to 26 April 1961 under the sponsorship of the Air Force Office of Scientific Research, several papers were given on the problem of neutralization of the space charge.

It is to be noted that one of these papers was by Dr. J. M. Sellen, Jr., in which he described an experiment in which he obtained neutralization of the beam. Dr. Sellen is from the Ramo-Wooldridge Laboratories of which Dr. David Langmuir is Director.

In two other ion engines, the one at Electro Optical Company and the one at the Hughes Aircraft Company laboratories, it is also claimed that the beam has been neutralized.

As a consequence, it was generally accepted at these meetings that the neutralization of the beam does not present anywhere near the difficulty that had been originally assumed, and at the present time this problem can be considered as solved.

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AF Cambridge Research Laboratories, Bedford, Mass. Electronics Research Directorate
ELECTRIC PROPULSION FOR SPACE VEHICLES, by Marcus D. O'Day. May 1961. 70 pp incl. illus.
AFCRL 357 Unclassified report

This report is a survey of the present status of electric propulsion in the United States. The writer defines electric propulsion as that where the momentum of the ejected material is due to the action of electric or magnetic forces acting upon the ultimate particles.

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